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IV. PESTICIDES

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The overall purpose of this report is to identify and evaluate Best Management Practices (BMPs) for reducing pesticide contamination of aquatic systems from agricultural nonpoint sources (nps). Since the 1950's pesticide inputs to water resources have become increasingly recognized as a serious, pervasive and yet largely unquantified problem. The report reviews documentation of pesticide-related water resource use impairments, and examines the transport modes of five major pesticide classes. This information is used to develop estimates of pesticide input reductions which can be accomplished by various classes of BMPs (soil and water conservation practices, improvements in application techniques, and intergrated pest management programs).

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IV. PESTICIDES

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EXECUTIVE SUMMARY

Since about the 1950's pesticide contamination of water resources has become recognized as a serious, pervasive yet largely unquantifiable problem of major ecological and public health concern. Although numerous case examples of water resource impairments have been reported, the present scope of the problem remains unclear due to 1) the intermittant and transient nature of pesticide inputs, 2) the often subtle ecological and human health effects of low level contamination, 3) rapid changes in pesticide types and usage patterns and 4) the extremely high expense of monitoring pesticide levels in aquatic systems. In spite of problem definition difficulties a few facts give some perspective to the dynamics of the problem:

1. Pesticides have been the leading single documented cause of fishkills in the U.S. over the past 20 years.
2. Evidence continues to accumulate on the acute, chronic and mutagenic human health effects of a growing number of pesticides at the part-per million and part-per billion levels commonly encountered in both ground and surface water.
3. Herbicide concentrations appear to be generally increasing in groundwaters in the U.S. concomitant with increased herbicide usage.
4. Aquatic biota, sediments, and agricultural soils continue to exhibit levels of banned organochlorine residues which are only moderately lower than ten years ago.
5. Estimates are that somewhere between 0.5% and 3% of the approximately 700 million pounds of pesticides used in the U.S. reach ground or surface water prior to degradation.

Appropriate strategies to minimize water quality impacts of pesticides are highly dependent on pesticide use trends. Overall insecticide use on major crops dropped by 46% between 1976 and 1982. The majority of the decrease is attributable to a 74% decrease in cotton applications brought about by IPM programs, application efficiency improvements and substitution with synthetic pyrethroids. Use

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of the persistent, highly toxic, and bioaccumulated pesticide, toxaphene, decreased 81% during this same period. In contrast, herbicide usage continued to increase especially in corn (15%) and soybean (35%) production systems.

Conceptually, there are three basic types of management options for reducing the water pollution potential of pesticide usage:

1. Reduce the amount of pesticide applied by:

    a) improving application efficiency

    b) using non-chemical (IPM) control measures

2. Substitute less toxic, less persistent or less mobile pesticides

3. Reduce or retard the transport of applied pesticides from fields to aquatic systems.

The most effective mix of management options is highly dependent on dominant transport modes for a particular pesticide class. The primary modes of transport to aquatic systems include: 1)direct application, 2)with surface or subsurface runoff, either dissolved, granular or adsorbed on sediment particles, 3)aerial drift, 4)volatilization and subsequent atmospheric deposition, 5)uptake by biota and subsequent movement in the food web.

The relative importance of these transport routes is influenced by many factors including the physical/chemical properties of the pesticide, the method and timing of application, weather and climate conditions and land characteristics (soil properties, slopes, crops). The major transport routes of the pesticide classes considered in this report can be summarized as follows:

1. Organochlorines (toxaphene).

    Volatilization - 20-90% depending on weather conditions. Drift - > 50% if aerially applied. Surface runoff - usually < 1% almost entirely in adsorbed phase. Biotic uptake small but highly significant for aquatic ecosystems.

2. Carbamates (carbaryl, carbofuran). These are lost from fields almost entirely in the dissolved phase of runoff. Some leaching through soil profiles is suspected but largely undocumented.

3. Organophosphorius insecticides - (methylparathion).

Volatilization - 20-90% depending on weather conditions. Drift - > 50% if aerially applied. Surface runoff losses occur in both dissolved and adsorbed phases with the relative magnitude dependent on the particular insecticide and soil type.

4. Triazine herbicides (atrazine, cyanazine).

   Volatilization - little information available. One study measured 40% from warm (35 C) soils. Drift - 0-40% depending on application method. Surface runoff - 0.2 to 16% depending on interval between application and first runoff event. Most loss is in dissolved phase. Leaching potential is significant. Numerous studies have detected triazines in groundwater.

5. Anilide herbicides (alachlor, propachlor).

   Volatilization and Drift - No information. Surface runoff losses - 1.0 to 8.6% almost entirely in dissolved phase.

6. Bipyridylium herbicides (paraquat).

   Volatilization - negligible. Drift - small but environmentally significant. Runoff losses - entirely in adsorbed phase - not generally biologically available.

The water quality effectiveness of various classes of pesticide Best Management Practices are summarized below:

1. Application efficiency improvement. (restricting aerial spraying, using larger drop sizes, restricting application when runoff events are predicted, applying only on windless days, evening or night spraying). These BMPs reduce pesticide transport by all routes but are particularly effective in reducing drift and volatilization losses.

2. Integrated Pest Management (IPM). These pest control systems significantly reduce the amounts of pesticide needed . A linear relationship between application rates and field loss is assumed. This assumption may err in either direction but is generally accepted. IPM systems reduce pesticide inputs to aquatic systems by all routes.

3. Soil and Water Conservation Practices (SWCPs). These practices affect runoff and soil leaching transport modes. For pesticides that are lost primarily in the sediment adsorbed phase, field loss reductions will

be somewhat less than erosion reductions because of pesticide enrichment on the more easily eroded fine sediment fraction. For pesticides lost primarily in the dissolved phase, loss reductions will be approximately equal to reductions in runoff volume. Some tradeoff is inevitable, however, between reducing surface losses and increasing soil leaching potential.

Conservation tillage systems are a special case as far as their effects on pesticide runoff losses. If the first rainfall event after application is relatively small, these systems exhibit dramatic reductions in pesticide losses relative to conventional tillage because little or no runoff is produced and the pesticide has an opportunity to be washed off the surface residue and into the soil. However, if the first post-application event is large, loss from these systems is greater than from conventional tillage because the pesticide intercepted by the surface residue is highly susceptable to transport.

4. Substitution of less toxic, less persistent or more selective pesticides.

The most obvious examples of this BMP are the restriction or elimination of persistent organochlorine insecticides, which continues to have a positive effect on aquatic ecosystems, and the substitution of synthetic pyrethroids. The synthetic pyrethroids are more selective, which enhances natural population control mechanisms, and they are applied at lower rates than the chemicals they replace. However, while field studies are lacking, laboratory studies show synthetic pyrethroids to be extremely toxic to many aquatic organisms.

The pesticide imput reductions to aquatic systems which can be accomplished using current BMP technology are summarized below for major U.S. crops.

Corn: Insecticide application can be reduced by 40-70% by greater use of crop rotations and field monitoring of insect populations. Surface runoff losses can be decreased by about 40% by SWCPs.

Soybeans: Soybean production has recently moved into new geographic areas where heavy insect and weed problems exist. The challange will be to prevent a proliferation of pest problems from indiscrete pesticide use. In the southeast and south-central U.S. pesticide usage can be kept at about its current level using IPM and improved application techniques. Losses to aquatic systems can be reduced about 40% using SWCPs.

Cotton: Insecticide use has decreased by 74% since 1976 as a result of IPM programs and the use of synthetic pyrethroids. Further, but less dramatic, reductions are possible. The use of toxaphene can and should be eliminated from cotton production. Reductions in herbicide usage of 30-40% should be possible using crop rotations, resistant varieties and more efficient (non-aerial) application techniques. Relative to potential use reductions and changes, SWCPs will have little effect (10-20%) on pesticide losses from cotton acreage.

Deciduous Tree Fruits: Reductions in pesticide use of 50-80% can be accomplished using currently available IPM technology.

Tobacco: Tobacco represents a small but intense source of pesticides to aquatic systems in the Southeast. Because of the inherent need for direct field drainage the delivery ratio of applied pesticides to aquatic systems is very high. The most effective improvements will come through IPM systems which can currently reduce pesticide use by about 30 to 60%.

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Chapter 1

INTRODUCTION

1.1 *BACKGROUND*

The agronomic importance of pest control, coupled with the increasing concern about the adverse side-effects of pesticides on public health and the environment, present a challenge to the agricultural community to develop pest control strategies which are more economical, effective over the long term, and less harmful to public health and the environment. The present report is intended to consider the tools available to address this challenge putting special emphasis on water quality considerations.

Shortly after World War II pest control shifted largely from a biological/ecological discipline to a chemical one. This era of dependence on pesticides (particularly insecticides) has provided good disease control, spectacular insect control, and more recently, adequate weed control (1). During the 1970's, however, a myriad of adverse effects resulting from over use or improper use of chemical pest control began to surface including:

1. The decimation of various predator bird populations as persistent organochlorine pesticides moved through the food chain (2);
2. The appearance of pesticide contamination in surface water, groundwater and aquatic ecosystems on a global scale;
3. The implication of a large number of pesticides as potent carcinogens (110);
4. The contamination of agricultural soils;
5. The massive destruction of non-targeted organisms resulting in the loss of natural pest population controls and the elevation of nonpest species to pest status (3);
6. The rapid evolution of resistant pest strains;

7. The neglect and consequent loss of crop varieties with natural resistance to pests.

Two outcomes of these adverse effects are that: (1) pesticides have been identified as the single leading cause of fishkills in U.S. surface waters, with 18% of reported incidents attributed to use of these chemicals (5): and (2) although the amount of pesticides used today is at least several times greater than in 1961, twice as large a share of U.S. crops are lost to pests (6). These statistics clearly point out the need for continued development of new pesticide management strategies to control pests effectively over the long term and to reduce adverse environmental impacts.

The term, pesticide, in this report is defined as any chemical or biochemical agent used to reduce organism-caused damage to crops, livestock or forests, including insecticides, herbicides, fungicides, nematocides and rodenticides.

The purpose of this report is to describe the factors and available research results relevant to selecting the most appropriate pesticide Best Management Practices (BMPs) and BMP systems. The intent is to optimize agricultural production while minimizing the water quality impact. To the extent possible the selection of pesticide BMPs is considered on a regional basis emphasizing the predominant crops and pesticides of each region. The review of the literature on each subtopic is not intended to be exhaustive due to the volume of literature available in the pesticide and pest management field. In addition, much of the literature in this area is in the form of University reports, state Extension Service Bulletins, and other non-reviewed publications of limited distribution. However, an attempt has been made to consider all refereed articles and reviews for each topic in the synthesis of the discussions and conclusions. The Southern Water Resources Information Service (SWRSIC) and AGRICOLA were the primary computer data bases surveyed as well as many other miscellaneous sources especially the National Water Quality Evaluation Project (NWQEP) Library System (144). The spatial placement of BMPs within a watershed to obtain maximum water quality benefits is not addressed in this report. This concept commonly referred to as targeting to critical areas, is fully addressed in another recent NWQEP publication (159).

Conceptually there are three basic options for reducing the water pollution potential of pesticide usage:

1. Reducing the amount of pesticide applied by:

    a) Improving application efficiency.

b) Using non-chemical control measures;

2. Substituting less toxic, less persistent or less mobile pesticides;

3. Reducing the transport of applied pesticides from fields to aquatic systems.

The BMPs available under Option # 1 generally include more efficient application methods in addition to a large array of biological management methods which in conjunction with traditional pesticides form what is known as Integrated Pest Management (IPM). Option # 2 generally involves the development of more selective and less persistent agents often termed 3rd or 4th generation pesticides. BMPs available under Option # 3 include improved application methods as well as a large variety of well-known soil and water conservation practices (SWCPs) which are designed to reduce sediment and runoff losses.

The transport of pesticides from application sites to aquatic systems is not fully understood; however, the primary modes appear to be direct dumping or spills, transport in overland runoff, transport in interflow (both to ground and surface waters), atmospheric drift into surface waters, deposition of air-borne soil particles with attached pesticides, and evaporation of pesticides from foliage or soil followed by subsequent redeposition (7). The relative importance of each of these transport mechanisms will depend on many factors including the physical/chemical properties of the pesticide, method of application, land characteristics, and climate. These factors will be discussed in depth in Section II on pesticide transport. SWCPs will generally affect only the fraction of pesticide lost in runoff (solid phase, adsorbed and dissolved) whereas pest control techniques which reduce the amount of pesticide applied will generally reduce pesticide losses through all transport routes (8).

1.2 *PESTICIDE USAGE*

In the context of optimizing pesticide management practices for water quality concerns it is important to understand actual current pesticide usage patterns. The pesticide usage data presented are taken from a USDA survey through 1982 (63). Table 1 shows both the total amounts of herbicides used by crop and the percentage of acres treated. These data show that herbicide usage is still increasing, and in fact, the total amount more than doubled in the 1971-1982 period. More significantly, the percentage of row crop acreage treated with herbicides has increased from 71 to 91 percent. Corn and soybeans account for 82 percent of herbicide use.

TABLE 1

Farm Herbicide Use by Crop, 1971, 1976, and 1982

Crop	Pounds of active ingredient (a.i.)			Proportion of acres treated		
	1971	1976	1982	1971	1976	1982
	-------Million--------			------Percent------		
Row crops						
Corn	101.1	207.1	243.4	79	90	95
Soybeans	36.5	81.1	125.2	68	88	93
Cotton	19.6	18.3	17.3	82	84	97
Grain sorghum	11.5	15.7	15.3	46	51	59
Peanuts	4.4	3.4	4.9	92	93	93
Tobacco	0.2	1.2	1.5	7	55	71
Total	173.3	326.8	407.6	71	84	91
Grain crops						
Rice	8.0	8.5	13.9	95	83	98
Wheat	11.6	21.9	18.0	41	38	42
Other	5.4	5.5	5.9	31	35	45
Total	25.0	35.9	37.8	38	38	44
Forage crop						
Alfalfa	0.6	1.6	0.3	1	3	1
Other hay	1/	1/	0.7	1	2	3
Pasture and range	8.3	9.6	5.0	1	1	1
Total	8.9	11.2	6.0	1	1	1
Total	207.2	373.9	451.4	17	22	33

1/ Quantity of herbicides applied to other hay is included in the alfalfa figure.

In Table 2 the same data are shown for insecticide use. In contrast to the trend for herbicides, insecticide usage has dropped dramatically since 1976. Most of this decrease is attributable to the increased use of more effective synthetic pyrethroids (chemical analogs of natural insect hormones), improved application efficiencies, and integrated pest management. Corn and cotton receive the greatest share of insecticides accounting for 66 percent of total usage.

TABLE 2

Farm Insecticide Use by Crop, 1971, 1976, and 1982

Crop	Pounds of active ingredient (a.i.) 1971	1976	1982	Proportion of acres treated 1971	1976	1982
	-------Million--------			------Percent------		
Row crops						
Corn	25.5	32.0	30.1	35	38	37
Soybeans	5.6	7.9	10.9	8	7	12
Cotton	73.4	64.1	16.9	61	60	36
Grain sorghum	5.7	4.6	2.5	39	27	26
Peanuts	6.0	2.4	1.0	87	55	48
Tobacco	4.0	3.3	3.5	77	76	85
Total	120.2	114.3	64.9	31	29	26
Grain crops						
Rice	0.9	0.5	0.6	35	11	16
Wheat	1.7	7.2	2.4	7	14	3
Other	0.8	1.8	0.2	3	5	1
Total	3.4	9.5	3.2	6	12	3
Forage crops						
Alfalfa	2.5	6.4	2.5	8	13	7
Other hay	1/	1/	0.1	**	2	**
Pasture and range	0.2	0.1	*	0	**	**
Total	2.7	6.5	2.6	**	1	**
Total	126.3	130.3	70.7	6	9	8

* = less tha 50,000 pounds (a.i).
** = less than 1 percent.

1/ Quantity of insecticides applied to other hay is included in the alfalfa figure.

Table 3 summarizes the total amounts of various insecticides and herbicides used in the U.S. for agricultural purposes. Although these figures do not precisely represent relative usage because they are do not consider differences in application rate, some interesting trends are still evident. Of the herbicides, alachlor, atrazine and butylate are the most heavily used. Atrazine has decreased in recent years while butylate has rapidly increased in importance. Many herbicide formulations are a mixture of atrazine and other herbicides. Usage of 2,4-D and propachlor on cropland has decreased greatly. However, 2,4-D is still widely applied directly to surface waters for control of aquatic macrophytes.

Carbofuran, methylparathion, and terbufos were the most extensively applied insecticides in 1982. Toxaphene dropped 81 percent between 1976 and 1982 with concurrent increases in synthetic pyrethroid usage. Organophosphorus class compounds made up the majority of usage (55%). Other pesticides, including dessicants, defoliants, fumigants, growth regulators and miticides accounted for another 30.2 million pounds or 5.5 percent of pesticide usage.

In planning BMPs for pesticides, information on the extent of usage for each crop is needed. Corn, soybeans and cotton account for approximately 82 percent of insecticide usage and 85% percent of herbicide use. Table 4 shows pesticides applied to corn in terms of acres treated and amounts applied. 'Acres treated' is probably a more accurate measure of extent of use than amounts applied because of differences in application rates. From Table 4 atrazine, alachlor, butylate and cyanazine account for the majority of herbicide used on corn. A wide variety of corn insecticides are applied with terbufos, carbofuran and fonofos the most predominant.
In Table 5 indicates that trifluralin (a dinitroaniline), metribuzen (a triazine), and alachlor (an anilide) are the most common herbicides on soybeans. Insecticide use on soybeans is very limited (12 percent of planted acres). The major types are methyl parathion, toxaphene, carbaryl and synthetic pyrethroids.

Table 6, which summarizes pesticide use on cotton, indicates that a wide variety of herbicides are used with trifluralin, fluometuron (a urea herbicide) and MSMA (an arsenical) accounting for two-thirds of cotton acreage. The most important insecticides include methyl parathion, synthetic pyrethroids and toxaphene.

TABLE 3

Total Farm Pesticide Use, 1971, 1976, and 1982

Pesticide	Pounds (a.i.)	Share of total	Pounds (a.i.)	Share of total	Pounds of (a.i.)	Share total
	1971		1976		1982	
Herbicides						
Alachlor	14.0	6.8	88.5	23.7	84.6	18.7
Atrazine	53.9	26.0	90.3	24.1	76.0	16.8
Bentazon 3/	--	--	--	--	9.9	2.3
Butylate+	5.6	2.7	24.4	6.5	54.9	12.2
Cyanazine 3/	--	--	--	--	16.6	3.8
EPTC+	3.4	1.6	8.6	2.3	8.3	1.8
Linuron	1.7	0.8	8.4	2.2	6.4	1.4
Metolachlor 3/	--	--	--	--	37.0	7.6
Propachlor	22.3	10.8	11.0	2.9	7.8	1.7
2,4-D	30.5	14.7	38.4	10.3	23.3	5.2
Trifluralin	10.3	5.0	28.3	7.6	36.1	8.0
All materials	207.2	68.4 1/	373.9	79.6	485.3	79.7
Insecticides						
Carbaryl	11.2	8.9	9.3	7.1	2.3	3.3
Carbofuran	2.8	2.2	11.6	8.9	7.3	10.3
Chlordimeform	--	--	4.5	3.4	0.7	1.0
Chlorpyrifos	*	*	*	*	5.1	7.2
DDT	13.5	10.7	--	--	--	--
EPN	0.9	0.7	6.2	4.8	1.4	2.0
Ethoprop	0.6	0.5	1.1	0.8	2.2	3.1
Fonofos	0.6	0.5	5.0	3.8	5.2	7.4
Methomyl	0.3	0.2	2.5	1.9	1.7	2.4
Methyl parathion	27.1	21.5	22.8	17.5	10.7	15.1
parathion	7.0	5.5	6.6	5.1	4.2	5.9
Phorate	3.6	2.9	6.3	4.9	4.0	5.7
Synthetic pyrethroids	--	--	--	--	2.6	3.7
Terbufos	--	--	2.5	1.9	8.7	12.3
Toxaphene	31.9	25.2	30.7	23.5	5.9	8.3
Dessicants and defoliants	17.4		8.6		9.4	
Fumigants	9.1		19.4		7.9	
Fungicides	6.4		8.1		6.6	
Growth regulators	5.0		6.3		6.0	
Miticides	1.1		1.0		0.3	
Other	32.5		35.3		--	
Total	405.0		582.9		552.3	

-- = none reported
* = less than 50,000 pounds (a.i.).

1/ Numbers in parentheses represent the shares of the total pounds (a.i.) of the materials listed individually.

2/ Does not include tobacco plant bed applications.

3/ From Agrichemical Age 26(8):1982.

TABLE 4

Corn Pesticide Use, 1976 and 1982

Pesticide	Acres treated (Million) 1976	Acres treated (Million) 1982	Pounds (a.i.) (Million) 1976	Pounds (a.i.) (Million) 1982
Herbicides				
Alachlor	34.3	26.4	58.2	52.3
Atrazine	56.9	47.9	83.8	69.7
Butylate+	8.2	14.9	24.3	54.9
Cyanazine	6.6	13.1	10.4	20.7
Dicamba	4.4	8.9	1.4	2.1
EPTC+	2.6	1.8	8.2	8.3
Linuron	1.2	0.4	1.6	0.3
Metolachlor	--	11.6	--	21.7
Propachlor	4.2	1.4	7.7	3.5
Simazine	1.8	3.3	2.4	3.3
2,4-D	12.5	11.3	8.0	5.1
Other	1.2	2.3	1.1	1.5
Total	133.9	143.3	207.1	243.4
Insecticides				
Carbaryl	2.1	0.1	2.1	0.2
Carbofuran	9.3	5.5	9.9	5.2
Chlorpyrifos	--	3.4	--	3.9
Dasanit	0.7	--	0.5	--
Diazinon	1.1	0.2	0.8	0.2
EPN	0.5	--	0.1	--
Ethoprop	0.2	0.7	0.2	0.7
Fonofos	5.5	5.6	5.0	5.1
Isofenphos	--	0.9	--	1.3
Methyl parathion	0.7	0.2	0.2	*
Organochlorines	3.2	--	3.9	--
Parathion	1.6	0.2	0.6	0.1
Phorate	6.1	3.7	5.8	3.8
Terbufos	2.2	7.7	2.5	8.7
Toxaphene	0.2	0.3	0.1	0.6
Other	0.5	0.8	0.3	0.3
Total	33.9	29.3	32.0	30.1
Fungicides	0.03	0.1	0.02	0.1
TOTAL	167.8	172.7	239.1	273.6

-- = none reported.
* = less than 50,000 acres.

1/ Includes nematicides.

TABLE 5

Soybean pesticide use, 1976 and 1982's

Pesticide	Acres treated		Pounds (a.i.)	
	1976	1982	1976	1982
		MILLION		
Herbicides				
Alachlor	18.7	18.3	30.7	30.7
Bentazon	5.3	11.6	3.8	8.0
Chloramben	3.7	4.4	4.4	5.9
Dinoseb	4.2	5.6	3.7	3.5
Linuron	10.4	8.3	6.2	5.8
Metolachlor	--	7.1	--	12.9
Metribuzin	8.5	23.6	5.2	10.2
Naptalam	3.1	3.3	3.9	4.4
Trifluralin	24.2	33.6	21.1	30.7
Other	3.9	19.9	3.2	11.9
Total	82.0	135.7	81.1	125.2
Insecticides				
Carbaryl	2.9	2.0	3.7	1.5
Disulfoton	0.2	0.1	0.2	0.1
Methomyl	0.9	1.7	0.5	0.7
Methyl parathion	0.7	3.4	0.7	2.6
Parathion	0.4	--	0.3	--
Synthetic pyrethroids	--	3.4	--	0.6
Toxaphene	0.5	1.9	2.2	3.7
Other	0.3	1.3	0.3	1.7
Total	5.9	13.8	7.9	10.9
Fumigants	0.5	--	2.0	--
Fungicides	1.2	0.2	0.2	0.1
TOTAL	89.6	149.7	91.2	136.2

* = less than either 50,000 acres or pounds (a.i.).
-- = none reported.

TABLE 6

Cotton Pesticide Use, 1976 and 1982

Pesticide	Acres treated (Million)		Pounds (a.i.)(Million)	
	1976	1982	1976	1982
Herbicides				
Cyanazine	--	0.7	--	0.6
Diuron	1.1	0.6	0.4	0.3
DSMA	1.2	0.6	1.5	0.9
Fluchloralin	--	0.3	--	0.3
Fluometuron	5.2	3.4	5.3	2.9
Linuron	0.9	0.4	0.4	0.2
MSMA	2.5	2.4	1.8	3.6
Norflurazon	--	0.6	--	0.5
Pendimethalin	*	1.0	*	0.6
Prometryn	0.9	1.0	0.7	1.0
Trifluralin	9.1	5.6	7.0	4.3
Other	2.3	2.1	1.2	2.1
Total	23.2	18.7	18.3	17.3
Insecticides				
Azinphosmethyl	0.4	1.0	0.2	0.6
Chlordimeform	2.9	2.3	4.4	0.7
Dicrotophos	0.8	0.6	0.3	0.2
Disulfoton	1.4	*	1.8	*
EPN	1.5	1.1	6.1	1.4
Methomyl	0.8	0.9	0.6	0.5
Methyl Parathion	6.2	3.8	20.0	7.2
Monocrotophos	1.5	0.4	1.5	0.3
Sulpofos	--	0.6	--	0.5
Synthetic pyrethroids	--	4.7	--	2.0
Toxaphene	3.1	0.6	26.3	1.2
Other	2.2	0.5	2.9	2.3
Total	20.7	16.5	64.1	16.9
Dessicants and defoliants				
Arsenic acid	0.4	0.5	1.7	2.2
DEF	2.3	1.5	3.4	1.7
Sodium chlorate	1.4	0.9	3.3	2.7
Other	0.03	0.7	*	0.4
Total	4.1	3.6	8.4	7.0
Fungicides	1.2	0.5	3.5	0.2
Miticides	0.5	0.1	0.4	0.2
TOTAL	49.8	39.4	94.7	41.6

-- = none reported.
* = less than either 50,000 acres or pounds (a.i.).

1.3 *OCCURRENCE AND EFFECTS OF PESTICIDES IN AQUATIC SYSTEMS*

1.3.1 *Occurrence*

1.3.1.1 **Ambient Studies**

Since concern about the occurrence of organochlorine insecticides in water, sediments and biota was first raised in the early 1960s, a tremendous amount of monitoring has been done to determine the distribution of pesticides in aquatic environments. Much of this information has been associated with the development of more sophisticated and sensitive analytical techniques and instrumentation for the determination of low-level contamination. A search of the literature identified more than 140 published studies and reviews describing the results of ambient water monitoring programs for pesticides since 1972 in the U.S. and Canada. Of these, approximately 20 addressed field runoff, 30 were concerned with ambient groundwater concentration, and the remainder related the occurrence of pesticides in surface waters.

It is difficult to draw overall conclusions on the significance of pesticide water pollution from the array of ambient monitoring studies, but a number of observations can be made:

1. Banned organochlorine insecticides such as DDT, dieldrin, and Endrin continue to be detected in agricultural soils, sediment, and aquatic organisms at levels only somewhat less than those found before restriction of their use.

2. The more biodegradable pesticides such as the organophosphorus and carbamate insecticides are found only sporatically in ambient studies.

3. Those herbicides of higher solubility or less strongly adsorbed to sediment may be generally increasing in frequency of occurrence in U.S. surface waters. There is, however, conflicting evidence on the extent to which their presence significantly disrupts the aquatic ecosystem. Many of these effects are subtle, intermittent and/or difficult to monitor.

4. Pesticides, whether from manufacturing waste water, field runoff loss, accidental spills or improper application were the largest single documented cause of fish kills between 1961 and 1974.

5. The majority of ambient groundwater studies have detected pesticides, particularly herbicides, in areas where agricultural use is extensive.

A recent study by Baker (157) indicated that herbicide concentrations in finished Ohio tap water were essentially the same as in the rivers receiving agricultural runoff used for water supply showing that conventional treatment does little to remove these contaminants.

1.3.1.2 Directed Studies

In an effort to determine better the severity of water pollution by pesticides a considerable number of directed plot or field studies have been conducted. These differ from the ambient monitoring studies in that they generally involve intentionally adding or varying the application rate of pesticides on crops or forests and observing subsequent pesticide concentrations in the aquatic ecosystem. The search of the recent literature identified about 80 such studies with approximately 40 directed to field runoff, six to groundwater and 31 to other surface waters.

A definitive review of pesticide concentrations in surface runoff from agricultural fields has been done by Wauchope (9). From 29 runoff studies involving 30 different pesticides a range of 0 to 18.3% of the applied pesticides was lost in runoff depending mainly on the type of pesticide, application method, slope, and application timing with respect to precipitation. The effects of these variables on pesticide transport are described in detail in Section II. For the majority of commercial pesticides the total losses to runoff were 0.5% or less of the amounts applied.

1.3.2 *Effects of Pesticides on Aquatic Systems*

1.3.2.1 Toxicity Studies

A tremendous volume of literature has been produced concerning the toxicity of various pesticides to aquatic organisms. There is an even larger body of research concerning the chronic or sublethal effects of pesticides on aquatic systems. The most complete source for pesticide toxicity information is the FDA Surveillance Index (155). This index is continuously updated, and is intended to evaluate the potential health risk of individual pesticides. Evaluations of 70 pesticides are currently included with each evaluation consisting of a summary of past FDA monitoring results as well as chemical, biological and toxicological data.

1.3.2.2 Effects on Water Quality

In addition to effects on aquatic ecosystems and biota the presence of pesticides can affect other physical/chemical water quality parameters. In the case of herbicides, the most commonly observed effect is a decrease in dissolved oxygen concentration caused by the decomposition of aquatic weeds exposed to herbicide-containing water (10,12.13).

The effects of pesticides on aquatic biota has been a subject of considerable interest. Of significance is the observation that algal photosynthesis is reduced by the presence of many herbicides and even some insecticides at concentrations well below accepted lethal or sublethal levels (11, 13). Herbicides which are more toxic to aquatic macrophytic plants than to algae may cause excessive algae growth as nutrients become available from decomposing vegetation (12). Many effects of pesticides on aquatic systems are subtle or indirect. For example, there is evidence that organophosphorus pesticides adversely affect ammonium oxidizing organisms in estuarine environments (14) allowing a buildup of ammonia which is toxic to fish.

Over 130 recent studies of effects of pesticides on aquatic macrobiota were identified. The effects vary widely with type of pesticide and organism. In many studies effects on the ecosystem were very subtle (behavior changes, elimination of ecological niches, creation of predator-prey imbalance or direct changes in water chemistry).

Chapter 2

MODES OF PESTICIDE TRANSPORT

2.1 *SELECTION OF MAJOR AND REPRESENTATIVE PESTICIDES*

Pesticide transport mechanisms are highly dependent on physical/chemical properties of the pesticide. Because these properties are generally similar within a class of pesticides, we, therefore, limit discussion to most widely used pesticides of each class. From an analysis of the data on pesticide usage presented earlier, combined with information on aquatic system impacts, the following pesticides and pesticide classes were selected as a focus for reviewing transport modes.

Insecticides:

1. Organochlorines (emphasis on toxaphene)
2. Organophosphorus (emphasis on methylparathion)
3. Carbamates (emphasis on carbaryl and carbofuran)

Herbicides:

1. Triazines (emphasis on atrazine)
2. Anilides (emphasis on alachlor)

Some transport information is also included on paraquat (because of its special role in no-tillage production). In addition, transport mode similarities with other important pesticides are noted where appropriate.

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2.2 *TRANSPORT TO AQUATIC SYSTEMS*

The primary routes of pesticide transport to aquatic systems are:

1. Direct application.
2. In runoff: either dissolved, granular or adsorbed on particulates.
3. Aerial drift.
4. Volatilization and subsequent atmospheric deposition.
5. Uptake by biota and subsequent movement in the food web.

The relative importance of each of these transport routes depends on many factors including the physical/chemical properties of the pesticide, the method and timing of its application, weather and climatic conditions, and the characteristics of the land (soils, slopes, crops etc.). The extent of soil adsorption and rate of degradation, in particular, have a strong influence on pesticide transport. A recent laboratory study by Rao et.al. (156) has determined adsorption coefficents and degradation rates as a function of temperature and soil moisture for several of the pesticide classes discussed below (carbamates, organophosphorus and triazines). For this discussion the physical/chemical characteristics of the pesticide have been chosen as the basis for initial consideration.

A thorough understanding of the dynamics of pesticide transport is an important key for selecting the optimal pesticide management strategy for a given situation. In most cases proper selection will be highly site-specific. This generalized review of the factors affecting pesticide transport is therefore intended to serve as a basis for more specific BMP selection guidelines.

2.2.1 *Organochlorine Insecticides*

Although most of these compounds have been banned from use in the U.S., as seen in Table 3 significant amounts of some materials, particularly toxaphene, are still in use. The need for selection of BMPs to reduce transport from previously treated fields is also still a legitimate concern (15,151).

2.2.1.1 Volatilization and Drift

In the case of toxaphene there is strong evidence that the principal mechanisms for field loss are aerial drift and volatilization. In windspeeds of 5.6 km/hr (3.8 mi/hr) it was found that only 47 percent of spray-formulated and only 14 percent of dust formulated toxaphene was deposited on cotton fields from aerial spraying (16). Dust formulations of toxaphene are not currently utilized because of this low delivery efficiency. Willis et. al. (17) observed that 26 percent of toxaphene applied to a mature cotton canopy volatilized within five days. Volatility rates were greatest during mid-afternoon peak temperatures, but volatility was also high when leaves were drying after heavy dew or light rain. Several other studies have shown similar or greater volatilization losses of organochlorine pesticides (18, 19, 20, 21). These studies indicate that the extent of volatilization is affected by air and soil temperature, humidity, and air circulation rates.

The impact of the volatilization transport route on aquatic systems has been difficult to document. It has, however, been estimated that aerial fallout may be a much greater contributor of toxaphene to aquatic systems than the more obvious field runoff. A 1976 study in the Mississippi Delta found high atmospheric concentrations of toxaphene and other pesticides in cotton growing areas (37). Toxaphene was present throughout the year with highest concentrations between June and October. Concentrations as high as 1946ug/m(3) were observed. Willis et. al. (17) estimated volatile losses were 3 or 4 times as great from a single application as runoff losses from the entire year.

2.2.1.2 Runoff and Soil Leaching

In a study of toxaphene washoff from cotton plants it was found that only an average of 1.3% of applied toxaphene was washed from the plant canopy by heavy simulated rainfall (22). This agrees well with Wauchope's estimate (9) that about one percent of applied organochlorine insecticide is lost in runoff waters. Within the runoff transport mechanisms it is generally agreed that most toxaphene is lost in the sediment phase rather than dissolved in runoff due to its low solubility (0.4 ppm) and strong soil adsorption properties (9, 8). Willis et.al. (151) observed that storm toxaphene yields were linear functions of storm sediment yields from a 18.7 ha watershed.

Because toxaphene is relatively insoluble and strongly adsorbed, the potential for groundwater contamination is low. One field study indicated that nearly all toxaphene was confined to the top 30cm of a Houston black clay after ten years (23). In another study, however, where excessive (100kg/ha) amounts were applied directly to a sandy-loam soil, toxaphene the underlying groundwater for the entire year of observation (24). Thus, the potential for toxaphene movement to groundwater appears to be present at least in the case of spills, improper application or land disposal.

2.2.1.3 Biotic Transport Modes

Uptake and movement through the food web deserves special mention as a transport mechanism for toxaphene. As with other organochlorine insecticides, the combination of slow biodegradability and high fat solubility result in uptake and biomagnification(increasing concentration with trophic level)in both aquatic and nonaquatic organisms. Although the actual percentage of toxaphene transported to aquatic systems through this route is not known and may be relatively small, it is this portion which may be most ecologically significant as nearly 100% of the pesticide transported by this route will directly impact aquatic biota. There is evidence that toxaphene is less biomagnified in aquatic ecosystems than other organochlorine insecticides (26).

2.2.2 *Organophosphorus (OP) Insecticides*

As shown in Table 1 the most common organophosphorus (OPs) insecticides in use are terbufos, fonofos and methyl parathion. The chemical structures of all three of these compounds are fairly similar, each being part of the class of compounds known as phosphoisothioates. With some exceptions, they have been found to have similar modes of transport.

A primary characteristic which differentiates the OPs from the organochlorines in terms of transport is their persistence in the environment. While the organochlorines have half-lives in the environment on the order of years, the OPs degrade relatively rapidly. Estimates of half-lives for different OP compounds, vary as do estimates for the same compounds, but most are in the range of 1-8 weeks depending on the contact medium (soil, atmosphere, water) (8, 27, 28). Thus, the transport of OP insecticides to aquatic systems and the subsequent impact on these systems are limited by the relatively short life of these chemicals.

2.2.2.1 Aerial Drift and Volatilization

As with the organochlorines, the principal modes of transport of OPs appear to be aerial drift during application and volatilization from plant and soil surfaces. Adair et al. found that when using methylparathion applied aerially from 1.52 meters, less than 40 to 50 percent of the applied material was deposited within the target area (29). Since most OPs are used on cotton which is often aerially treated, this represents a major transport mode. A review by von Rumker et. al. (30) indicates that similiar losses from drift occur from aerial spraying of any insecticide. Ultimately, however, the percentage of drifted material which reaches aquatic systems and the resulting aquatic concentrations depend on the proximity and morphology of downwind water bodies.

Volatilization is also a very important transport mechanism for OPs. Reviews by Hague and Freed (21) and Spencer et. al. (31) indicate that between one-third and one-half of OPs that reach the target area volatilize. The actual amount depends on temperature (32), humidity, air circulation, and soil moisture (33). In hot weather regions such as the cotton growing areas of Mississippi half-lives of methyl parathion on soil and plants have been observed to be as low as one-half hour (34). Atmospheric OPs may be found in vapor phase or adsorbed (35). A number of studies have detected atmospheric concentrations of OPs both in treated and untreated areas (36, 37, 35). From these it can be concluded that while airborne residues are invariably found near sprayed areas during the growing season, their presence also covers large areas remote from treatment. Unlike toxaphene, atmospheric methyl parathion was observed at significant levels only during July, August and September because of its more rapid biodegradation (37). However, very high atmospheric concentrations (up to 2060ug/m{3}) were observed during these three months. The impact of OPs on aquatic systems through the volatilization mode of transport is difficult to assess because of the diffuse nature of the input. Studies of concentrations in rainfall are necessary to determine whether redeposition is a significant source of OPs and other pesticides to aquatic and terrestial ecosystems.

2.2.2.2 Runoff and Soil Leaching

While the amount of OPs available for transport to aquatic systems through runoff and leaching is greatly limited by drift and volatile losses and by the relatively quick degradation rates of these compounds, runoff losses may be harmful to aquatic systems because they enter the system as concentrated pulses. Also, little information is available on whether some degradation products may also damage aquatic ecosystems. Wauchope (9) cites a range of 0.008% to 0.25% of applied methylparathion lost in runoff. A Canadian study showed high parathion loadings in drainage waters from nearby agricultural lands where high application rates were used (38). No attempt was made to quantify what percentage of material was being lost by this route however. It would appear that the percentage of materials lost in runoff (adsorbed or dissolved fraction) is indirectly, but perhaps strongly, correlated with soil type because soil type has been shown to affect the persistence of OP compounds in soil. For example, the persistence of parathion in soils is increased by the presence of clays, organic matter or low pH (35). Baker et. al (55) found that the OP, fonofos, was lost primarily in the adsorbed phase, and losses could be reduced by erosion reducing tillage methods. Modeling efforts for methylparathion predict that about 90 percent of runoff losses are in the dissolved phase (143).

2.2.2.3 Leaching to Groundwater

Some information exists on the leaching of OPs through the soil profile to groundwater. The moderate solubilities and moderate soil adsorption coefficients for these compounds place them in a low to intermediate range for groundwater contamination potential. Field studies have shown leaching of parathion through 12-18 inches of soil profile (39,40). King and Mc Carty (41) have shown that the leaching of parathion is greatly influenced by soil type with considerably less leaching occurring on clay soils.

2.2.3 *Carbamate Insecticides*

As shown in Table 1 the most heavily used insecticides of this group of chemicals are carbofuran (on corn) and carbaryl (on soybeans). These compounds are both methylcarbamates, and are therefore structurally similar. However there are some differences in chemical properties which result in somewhat different modes of transport. One example is the difference in solubility (42) (carbofuran = 700 ppm, carbaryl = 40 ppm) which has important implications for runoff transport. Another is vapor pressure (carbaryl>carbofuran) which affects volatile losses.

2.2.3.1 Runoff and Soil Leaching

Despite the differences in solubility, research results indicate that both carbamates are lost almost entirely in the dissolved phase of runoff (43). Because of its higher solubility carbofuran is more susceptible to runoff losses. Over a period of three months covering eight runoff events only 0.15% of applied carbaryl was lost (43), while other studies by Caro et. al. (44) have shown seasonal runoff losses of carbofuran ranging from 0.47 to 1.9 percent on silty loam soils. Studies on claypan soils showed annual maximum losses from single runoff events ranging from 1 to 14% of applied carbofuran (45). Runoff concentrations ranged from 298 to 600 ppb. Because the 96-hour LC(50) ranges from 80 to 1180 ppb for ten fish species, runoff losses of these magnitudes clearly constitute a serious threat to neighboring aquatic ecosystems (8).

2.2.3.2 Drift and Volatilization

Airborne losses of carbofuran either from drift or volatilization are considered to be quite small. This is due to both low vapor pressure (6.5x10-5 torr) and the fact that carbofuran is usually applied to the soil in a granular form. Even with granules drift losses can be significant (up to 50%) if application is made under windy conditions (12 mi/hr) (8). There is no evidence of volatile losses of carbofuran when applied for agricultural purposes regardless of application method or timing.

Airborne losses of carbaryl can be quite high. Its vapor pressure of 2.1x10-5 torr makes it about 3 times as volatile as carbofuran. Stewart et. al. (46) classified carbaryl as only slightly less volatile than methyl parathion or toxaphene, indicating that volatile losses in the range of 10-30 percent might be expected. In addition, carbaryl is frequently applied as a dust formulation which makes it susceptible to large drift losses whether applied by aerial or ground equipment.

The carbamates are fortunately very short-lived in the environment, a consideration which lessens the effect of their acute toxicity to aquatic organisms. Carbaryl has been shown to persist for up to three weeks in soil (47) and one - two weeks in aquatic systems (28). Carbofuran is longer-lived in soil systems (16 weeks) but is degraded as rapidly as carbaryl in aquatic systems (48)

Movement through the food web is not considered an importent transport mechanism for carbamates because of their rapid biodegradation and fat insolubility. Another study showed that the aquatic degradation of carbaryl by hydrolysis is very pH and temperature (Q_{10}=2.9) dependent. Little hydrolysis occurs at pH 6, whereas the half-life varies from 10.5 days at pH 7 to 1.3 days at pH 8 (142).

2.2.4 *Triazine Herbicides*

Triazine herbicides include such products as atrazine, cyanazine, metribuzin, prometryn, propazine, secbumeton, simazine, and terbuthylazine. Of these atrazine is by far the most extensively used on cropland, and thus will be emphasized in this discussion of transport modes.

2.2.4.1 Runoff and Soil Leaching

Runoff losses of triazine herbicides from cropland have been a major concern and have been studied under a wide variety of conditions. Wauchope (9) cites a range of 0.2 to 16% of applied atrazine lost in runoff depending on conditions. The most important factors affecting runoff losses appear to be topography and soils (49,50), land management practices (51,52,53), rainfall, intensity (53), application rates, and, perhaps most importantly, the time interval between application and subsequent runoff events (54,51). There is evidence that other factors such as soil pH and organic matter content may also influence runoff losses by affecting the partitioning between adsorbed and dissolved phases (50). Atrazine is more strongly bound by organic matter and acidic soils.

Although the concentration of atrazine is invariably higher in the adsorbed phase of runoff, there is general agreement that the majority of atrazine is lost in the dissolved phase due to the high ratio of water to sediment in runoff from cropland (54,49,52). Hall (54) observed that eight times more atrazine was lost in the soluble phase than in the adsorbed phase of runoff at a 2.2 kg/ha application rate and over four times more at a 4.4 kg/ha rate. In these field studies about 90% of the runoff loss of atrazine occurred during the first month after application. Studies by Baker and Johnson (53) indicate that seasonal losses can be kept under 5 percent in years when the application-runoff interval is greater than two weeks. Losses were 16 percent when a storm occurred immediately after application.

Ritter et. al. (51) noted that much more atrazine was lost from surface-contoured fields than from ridge-contoured fields. Baker et. al. (55) found that cyanazine losses were virtually identical from either conventionally tilled plots or from a series of plots in various forms of conservation tillage (till-plant, chisel plow, disk-plant, ridge-plant and fluted coulter). The decreases in runoff volume and soil loss from the conservation tillage systems were negated by the increased cyanazine runoff concentrations. This was attributed to the effect of surface residue intercepting the herbicide spray before it could reach the soil surface, thus preventing soil adsorption. This is substantiated by the work of Martin et. al. (148), who found that 32 to 43 percent of triazines or anilides were washed from corn residue by 5mm (0.2 in) of simulated rainfall. Other studies (56,57) have noted greater atrazine losses from no-till plots versus conventional tillage for the same reasons. In contrast Triplett et. al. (52) observed somewhat lower losses from no-till corn. Triplett et. al. (52). surmised that this was due to moderate intensity storms which produced no runoff from several of the no-till plots. The other studies used high intensity simulated rainfall. Likewise, in a recent three year natural rainfall plot study, Hall et.al. (149) found that cyanazine runoff losses were reduced between 85 and 99 percent from no-till verses conventionally till corn. In this case, the large reduction were attributed to the use of a "living mulch" surface of crownvetch and birds foot trefoil which minimized the residue interception problem. The effect of surface residue on herbicide runoff is further clouded by a more recent plot study by Baker et. al. (126) which showed that herbicide runoff losses were consistently less from plots with surface corn residue. There was no significant difference in runoff loss between plots where atrazine and alachlor were applied over the residue or where the herbicides were applied first and then covered with residue.

A recent discussion by Baker and Laflen (147) explains these seemingly conflicting results. They note that, if herbicide application on crop residue is followed by a light rainfall, herbicides washed off the crop residue infiltrate into the soil making them less susceptible to loss in future runoff events than herbicides applied to bare soil. If, on the other hand, an intense runoff-producing storm is the first event after the herbicide application, then more herbicides will be lost from reduced tillage than from conventional tillage because the free herbicides washed from the crop residue will be very readily carried in surface runoff.

In one of the very few actual watershed studies on atrazine inputs to aquatic systems Wu et. al. (145) found annual atrazine stream loading rates ranging from 1.2 to 2.7 g/ha for seven 16 to 254 ha watersheds. These loading rates represented 0.05 to 2.0 percent of the amounts applied. In contrast to several of the field and plot studies atrazine was detected in stream flow from runoff events throughout the year. In fact, in the drought year of 1977 the majority of stream input occurred during the following winter and spring (i.e. 6 to 9 months after application). Also of significance was the finding that daily flow weighted mean concentrations in the streams never exceeded 40 ug/l during the three years of study, and monthly flow weighted means ranged from <0.01 ug/l to 8 ug/l, much lower concentrations than generally observed from plot and field studies.

A summary of atrazine runoff losses is shown in Table 7. Of particular significance is the range of runoff water herbicide concentrations observed in these studies. While atrazine is considered only moderately toxic to fish, concentrations in the 0.02 to 0.5 mg/l range have been shown to disrupt aquatic ecosystems by eliminating phytoplankton and submerged macrophyte species (58,150).

The potential for groundwater contamination by triazines has also been a major research concern in recent years. Several groundwater monitoring studies have revealed the widespread presence of these compounds at detectable levels (59,60). The extent to which leaching occurs depends on several factors including the application rate, soil composition, soil moisture, plant uptake, and management practices (8).

In soil column leaching experiments atrazine penetrated six to eight inches in two days with maximum movement occurring in light textured sandy loams at high pH (61).

A field study (97) with well-drained sandy loams in Nebraska found atrazine levels ranging from 0.01 to 8.29 ug/l in groundwater 5 to 10 meters below irrigated corn. Seasonal fluctuations indicated some soil dissipation of atrazine. Laboratory studies ruled out microbial degradation as a significant dissipation mode.

The adsorption of atrazine is maximized by the presence of soil organic material and acidic clay soils (50). Scott and Phillips (62) determined that the movement of atrazine through a silty clay loam increased by a factor of four as soil moisture content was increased from 25 to 38% indicating the strong influence of soil moisture on leaching potential.

2.2.4.2 Drift and Volatilization

Drift losses of atrazine depend almost entirely on the application method, ranging from negligible for incorporated ground equipment application to about 40 percent when aerially applied (8, 30). Even applications by ground equipment

TABLE 7

Atrazine Runoff Losses Summary

Amount Applied (Kg AI/ha)	Type Application	Average Slope (%)	Loss in Runoff (% Application)	Concentration in Runoff Water (ppm)
3.36[1]	surface with simulated rainfall[a]	6.5	2 (2 - 7.3)	0.16-8.08
2.2[2]	surface[b]	14	2.5	0.0-0.8
1.68[1]	incorporated with simulated rainfall[c]	2.2	6.44	0.0-3.3
1.68[1]		3.6	12.47	0.0-7.9
3.36[1]		2.5	13.3	0.0-11.1
3.36[1]		5.7	10.18	0.0-4.0
2.2[2]	surface[d]	14	5.0	0.0-2.3
4.5[2]			4.8	0.05-4.6
3.36[3]	surface[e]	10-15	2.7-16.0	1.17-4.91
2.24[2]	surface[f]	12-18	>5 (>5-15)	---
1.12-3.36[2]	incorporated[g]	8-22	0.02-5.7	0.10-0.48
2.09[2]	surface (0)[4]	5	5.71	0.14
2.09[2]	with (375)[4]	5	3.37	.10
2.09[2]	simulated (750)[4]	5	2.54	0.09
2.09[2]	rainfall[h] (1500)[4]	5	0.97	0.09
3.36[5]	incorporated[i]	4	1.9	0-0.20
3.81[5]		4	0.2	0-1.90
1.54[5]		4	0.7	0-0.10
3.36[5]		3	0.8	0-0.16
4.03[5]		3	0.2	0-0.33
1.45[5]		3	0.3	0-0.04
1.7[6]	surface[j]	5	0.37	-
1.0[6]		5	0.18	-
1.0[6]		5	0.14	-

[1] Duration of experiment was 1 hour on fallow lands.
[2] Duration of experiment was 5 months on corn crop.
[3] Duration of experiment was 58 days on corn crop.
[4] Kg/ha corn residue.
[5] Duration of experiment was 90 days on corn crop.
[6] Duration of experiment was 1 year on corn crop.
[a] White *et al.* (1967).
[b] Hall *et al.* (1972).
[c] Bailey *et al.* (1974).
[d] Hall (1974).
[e] Ritter *et al.* (1974).
[f] Baker and Johnson (1977).
[g] Triplett *et al.* (1978).
[h] Baker *et al.* (1982).
[i] Leonard *et al.* (1982).
[j] Wu *et al.* (1983).

can lead to drift losses of 50 percent under windy conditions (53).

Little information exists on volatile losses of triazines. The greatest amount of volatilization appears to occur when application is to the surface rather than incorporated and when application is made to dry, warm soils (8). The extent of volatilization appears to be very temperature dependent. One study measured losses of 40 percent and 80 percent at soil temperatures of 35 c and 45 c respectively (64).

Atrazine and other triazines kill weeds by inhibiting photosynthesis. This mode of action creates the potential for subtle aquatic ecosystem effects by eliminating sensitive algal and macrophytic species (160). Atrazine has been shown to be toxic to fish in the 0.5 to 10 ppm range (65) within which fall runoff concentrations observed under worst case conditions.

The persistence of atrazine in the environment depends on several of the factors previously mentioned in connection with transport routes including: method of application (surface applied or incorporated), soil conditions and application rate. Hague and Freed (21) have noted persistence in soil of four months to a year. Greater persistence was noted when the material was incorporated in acidic or organic soil. Persistence increases with the clay content of the soil and serious carryover problems can occur from one crop season to the next when the clay content is greater than 30 percent (70). Recent work by Gressel et. al. (66) has shown that N-dealkylaton by triazine resistant plants may be a primary degradation route. Little information on persistence in aquatic systems is available, although as opposed to soil systems photodecomposition and hydroxylation are believed to be the major degradation mechanisms (67). There is evidence that significant decomposition of atrazine occurs by hydrolysis reaction in acidic waters (68). There is general agreement that triazines are not biomagnified to any appreciable degree, with the greatest accumulation noted in certain species of triazine resistant algae (8, 69).

In summary, the persistence and degradation of atrazine, and to some extent other triazines, in agricultural soils are fairly well understood, but less is known about their persistence in aquatic environments. The degradation rate in aquatic environments has important implications for designing management practices to control pollution by triazines. Based on the frequent detection of atrazine in surface and groundwaters, there is little reason to believe that it is less persistent in aquatic systems than in soil systems. Therefore, management practices to control triazine inputs to aquatic systems need to be effective through entire seasons.

2.2.5 *Anilide Herbicides: Alachlor, Propachlor*

As noted in the discussion on pesticide usage, alachlor has become a major herbicide on both corn soybeans and its use appears to be increasing rapidly on both crops (71). In contrast usage of propachlor has dropped by almost 75 percent since 1971 (Table &3.). A search of the literature revealed very little research information on alachlor transport mechanisms.

Alachlor's solubility in water is 242 ppm or nearly eight times higher than atrazine. On this basis it would be expected that, like atrazine, most runoff losses would be in the dissolved rather than the adsorbed phase. Research by Baker et. al. (55) has verified this assumption. Bulk (dissolved plus adsorbed) runoff concentrations ranged from 75 to 184 ug/l with sediment concentrations of about one mg/l from small plots with simulated rainfall. An average of 7.9 percent of the applied amounts were lost. Tillage practices had no significant effect on runoff losses. Baker et. al. (126) observed alachlor losses in surface runoff ranging from 1.0 to 8.6 percent from heavy simulated rainfall with losses decreasing with increasing crop residue. Percentage losses were somewhat greater for alachlor than for atrazine on the same plots. The solubility of propachlor is 580 ppm giving it even greater potential for loss in the dissolved phase and leaching to groundwater. Ritter et. al. (51) found that 3.1 percent of applied propachlor was lost in runoff in the first month following application. Bulk runoff concentrations were as high as 1.7 ppm.

The small watershed studies by Wu et. al. (145) showed very small watershed losses of alachlor (<0.1 percent). Overall stream loadings were lower than for atrazine even though alachlor was used at higher rates in the watershed. Stream concentrations of alachlor seldom exceeded 1ug/l. Alachlor is normally applied either in granular form or as an emulsion applied to the soil surface. No information was found on drift or volatile losses of alachlor or on its soil leaching behavior.

2.2.6 *Bipyridylium Herbicides: Paraquat*

Paraquat deserves special mention because of its role in conservation tillage and no-till corn production since the acreages under these practices are large and are projected to increase dramatically in the near future. Paraquat's role in conservation tillage systems is to destroy either cover crops or growing annual weeds at crop planting or prior to emergence.

A series of field experiments by Smith et. al. (72) showed a range from 0.9 to 18.3 percent of applied paraquat lost in runoff. This is probably a large overestimation of runoff losses because the application in these experiments was directly to soil, while in agricultural use, application is primarily to foliage. Another study revealed runoff losses of 1.28 percent (73). All losses were in the sediment bound phase, because as a positively charged ion, paraquat is strongly bound to the negatively charged soil particles.

Paraquat is usually ground applied with water or liquid fertilizer at 30 to 50 gal/acre. Large droplet sprayers are used to minimize the amount of drift (8). Byass and Lake (74), however, have shown that drift losses of paraquat of only 0.1 percent of the applied amounts could cause damage to down-wind plants. Paraquat is essentially nonvolatile, and volatilization losses from agricultural fields are negligible (75).

The complex question of whether paraquat adversely impacts aquatic systems has been well addressed by Shoemaker and Harris (8). Although paraquat in its free form is highly toxic to both plants and animals, it is rapidly and apparently permanently bound to clay materials in soil or sediments. There is strong evidence that clay-adsorbed paraquat is not biologically available. With the exceptions of soils with very high organic or sand content even the least adsorptive soils can strongly bind many years of paraquat applications (76). Erosion and transport of such paraquat containing soil particles to aquatic systems could cause contamination until the available paraquat was redistributed onto deactivating clays. Although runoff losses of paraquat are substantial, no documented cases of adverse impacts of paraquat in aquatic systems have been reported. It has been assumed that leaching of paraquat through the soil column can not occur because of the strong soil adsorption. However, recent work by Vinten et. al. (125) shows that paraquat can move a considerable distance through the soil if adsorbed to mobile clay colloids. The researchers suggest that this same transport mechanism is also possible for other soil adsorbed pesticides.

Thus, field losses of paraquat appear to be relatively innocuous to aquatic systems providing little incentive for control. The greatest hazard from paraquat use appears to be to farm workers and to applicators who might be exposed to unbound paraquat from handling and drift.

Chapter 3

BEST MANAGEMENT PRACTICES FOR REDUCING PESTICIDE DELIVERY TO AQUATIC SYSTEMS

Having established the modes by which various classes of pesticides are lost from agricultural lands and reach aquatic systems, and having discussed the subsequent impact on these systems, it is possible to consider the agricultural options available for protecting water quality. Agricultural options for pesticide pollution control fall into four general categories:

1. Soil and Water Conservation Practices (SWCPs);

2. Increasing efficacy of pesticide application techniques;

3. Integrated Pest Management systems which minimize the amounts of pesticides needed (IPM);

4. Substitution of less biotoxic and/or less persistent pesticides where effective alternatives exist.

The remainder of this section provides a brief discussion of how each of the four classes of pesticide pollution control options listed above can function to reduce pesticide losses to aquatic systems. With this background, an analysis of optimal best management system approaches will be presented for some major U.S. agricultural crops (corn, soybeans, cotton, tobacco, alfalfa and tree fruits).

3.1 *SWCPS*

3.1.1 *Non-structural Practices*

3.1.1.1 Conservation tillage

The largest and most important controversy regarding the pesticide pollution control effectiveness of SWCPs has centered around conservation tillage systems. There appears to be agreement that into the near future these systems may require somewhat greater pesticide usage (particularly herbicides) than conventional tillage systems (78). Counteracting the greater pesticide usage are the reductions in soil loss and often in runoff volume which accompany these practices. A recent review of sediment control practices (77) indicates that conservation tillage systems reduce soil loss by 60 to 99 percent depending on such factors as percent surface coverage, soil type, slope, and crop. No-till reductions normally range between 85 and 99 percent. Thus, strongly bound pesticides such as paraquat and toxaphene, which are lost primarily in the sediment-adsorbed phase of runoff, should be sharply reduced by conservation tillage. As with other sediment-bound materials such as phosphorus, loss reductions are predicted to be less than soil loss reductions because the soil particles which are lost from SWCPs are the finer fractions which have relatively greater amounts of adsorbed materials (77,151).

Runoff volume is usually reduced by conservation tillage systems. Changes have been reported to range from -89 percent to +10 percent. No-till systems reduce runoff volume less than other conservation tillage systems, and in a few cases no-till runoff volumes have been greater than from conventional tillage (77). On this basis it would be expected that runoff losses of pesticides that are primarily in the dissolved phase, such as carbamates, triazines and anilides, would usually but not always be significantly reduced. However, as noted earlier, in several studies equal or greater amounts of triazines were lost from conservation tillage than from conventional tillage (55,56,57). The expected control of pesticide loss from control of runoff and soil loss is often negated by higher concentrations in the runoff. Surface residue may intercept a portion of the pesticide application before it reaches the soil surface, thereby rendering it more susceptible to runoff loss. Also, in these experiments application rates were identical for conventional and conservation tillage plots whereas recent work shows that for corn and soybeans more herbicides may be used in conservation tillage systems, particularly notill (Table 8) (78).
These data show that, while no-till herbicide usage is considerably greater than conventional, there are no significant differences in overall herbicide use between other reduced tillage systems and conventional systems for corn or soybeans. As noted earlier, conservation tillage systems necessitate different herbicide use patterns (use of contact herbicides and broad spectrum herbicides). Also, conservation tillage systems often preclude the possibility of incorporating pesticides into the soil. Therefore, the pesticides are more readily available for transport in runoff. Higher application rates may be necessary to achieve proper pest control. This latter effect is seen in the control of root-worm infestation in corn where insecticide application rates are considerably higher for no-till systems.

TABLE 8

Per-Acre Herbicide Cost for Corn and Soybean Production By Tillage System

Corn: Ten Major Producing States			
No-till	3.50		
Reduced-till	3.38		
Conventional-till	3.00		
Soybeans			
	Midwest	Midsouth	Southeast
No-till	3.23	2.00	1.68
Reduced-till	1.86	1.74	1.46
Conventional-till	2.03	1.45	1.38

3.1.1.2 Contouring

Contour farming reduces soil erosion by slowing water movement and allowing increased infiltration. It is most effective on fields of moderate (<8%) slope which are free of depressions and gullies. Runoff volumes may be reduced 15 to 55 percent depending on crop and soil type (83). Similiar reductions of dissolved pesticides would be expected, however, a study in western Iowa found that nutrient reductions relative to noncontoured fields were somewhat less than runoff reductions (80). This suggests that the degree of runoff reduction may constitute an upper limit for surface runoff reduction of pesticide transported in the aqueous phase of surface runoff. Another study (51) found that atrazine loss was greatly reduced by both surface and ridge contoured fields relative to noncontoured fields. Greater reductions were noted for ridge-contoured fields which allowed more "ponding" of runoff between rows with subsequent increases in infiltration. The increased infiltration from contouring may increase the potential for groundwater contamination for those pesticides which are relatively mobile in soil.

3.1.1.3 Stripcropping

Stripcropping has potential advantages for reducing pesticide runoff losses by reducing erosion and runoff volumes. The extent of reduction is dependent on soil type, slope, types of crop and the presence of complementary SWCPs. In addition, there is evidence that stripcropping can reduce insect, nematode, and weed problems, thus affecting the amounts of pesticides required (114).

3.1.1.4 Grassed Waterways

Grassed waterways can be considered either structural or nonstructural depending on how much earth-moving is required for construction. The primary function of grassed waterways is to prevent the formation of gullies in natural or constructed field depressions which transport surface runoff from the field. In this capacity they should have little effect on pesticide losses because pesticides are generally not directed to the waterway. A secondary function of grassed waterways is to slow runoff velocity allowing sediment deposition within the field and to otherwise filter sediment particles from runoff (77). In this capacity some reduction in sediment-adsorbed pesticides would be expected.

3.1.1.5 Cover crops

The purpose of cover crops is to provide vegetative cover and erosion control during the nongrowing season. The extent of erosion control obtained depends on the precipitation patterns of a particular region during the nongrowing season and on the amount of cover crop establishment before winter freeze. In northern areas or after late crops like soybeans, little fall growth occurs and cover benefits may be negated by the additional fall tillage often necessary. Large-scale studies in the Black Creek, Indiana project (81) documented some erosion reduction from cover crops in this region. A Missouri study found that a rye cover crop with no-till corn reduced soil loss by over 95 percent compared to conventional- till continuous corn (82). This probably represents the upper limit of possible erosion reductions from the practice. Runoff volumes should also be reduced both as a function of increased infiltration and evapotranspiration by the cover crop, although no quantitative data are available. A search of the literature found no actual field studies which determined effects of cover crops on runoff losses of pesticides; however, from the discussion above it would be expected that losses could be somewhat reduced for pesticides lost either in the sediment-adsorbed or runoff phase which are sufficiently persistent to still be available for loss into the nongrowing season.

3.1.1.6 Filter Strips

Filter strips have little or no effect on erosion but can reduce the sediment delivery ratio to aquatic systems by slowing runoff velocity and filtering sediment. Karr and Schlosser (42) found that vegetative filters could effectively filter sediment from both sheet and shallow channel runoff. Their sediment holding capacity is very limited and thus must be used in conjunction with erosion-reducing practices to be effective. Variables which affect their utility include: filter width, degree and homogeneity of slope, vegetative type, sediment size distribution and concentration, and runoff application rate (83). On this basis filter strips could be expected to reduce the delivery of sediment-bound pesticides to aquatic systems.

3.1.2 *Structural Practices*

3.1.2.1 Terraces

Terraces are structures consisting of a combination ridge and channel constructed across the slope (83). They can be divided into two general classes: graded terraces which divert water to a grassed waterway or to some other nonerosive drain; and level terraces which hold water on the field increasing infiltration and allow eroded soil to be redeposited. The range of soil loss control achievable by terracing has been observed to be 50 to 98 percent depending on climate, slope and soil type (77). Similar reductions in runoff volumes have been observed with greatest reduction occurring in drier areas with level terraces. It has been noted that terraces should reduce losses of strongly adsorbed pesticides such as paraquat and organochlorine insecticides and that the degree of sediment reduction should be an upper limit (72). A study in western Iowa on pesticide loss from terraces and contoured fields produced results which suggest that less discharge of moderately adsorbed pesticides such as atrazine and organophosphorus insecticide occurred from terraced watersheds than from contour planted watersheds (84). Most terracing is constructed on long, moderately steep slopes where much of the infiltration reappears as stream baseflow. Therefore, while edge of field dissolved pesticide losses may be reduced concomitant with runoff volume reductions, the extent to which actual pesticide inputs to nearby aquatic systems are reduced is unknown.

The increased infiltration accomplished by terracing greatly increases the potential for pesticide leaching to groundwater, particularly in more humid regions such as the Northeast, Southeast and Pacific Northwest.

3.1.2.2 Sediment Basins

Sediment basins have no effect on edge of field soil loss but have been shown to be highly effective in trapping sediment particles before they can reach water resources of ecological, economic or recreational importance. The Black Creek Indiana project (81) showed that sediment basins could effectively trap fine particles which are the most difficult to control on the field (less than 50 microns in diameter). Several other studies have found a range of 65 to 98 percent efficiency in sediment trapping (85,86,87) depending on mean flow velocity, particle size distribution and reservoir geometry.

Clearly, sediment basins primarily affect sediment adsorbed pesticide inputs. Their effect on dissolved pesticide transport will depend on the relative magnitude of the basin detention time and the aquatic half-life of the pesticide. Some additional pesticide removal may occur as a result of uptake and/or degradation by biota within the sediment basin (89,90). A search of the literature found no studies on the pesticide removal efficiencies of sediment basins receiving cropland runoff. Sweeten and Drire (88), however, observed that evaporation ponds adjacent to Texas feedlots effectively reduced pesticide loss in feedlot runoff.

3.1.3 *Summary of Effect of SWCPs on Pesticide Inputs to Aquatic Systems*

A summary of the effects of various SWCPs on surface runoff volume, soil erosion and sediment delivery ratio is shown in Table 9. Practices which reduce sediment inputs to aquatic systems either by reducing erosion or reducing the sediment delivery ratio will decrease aquatic inputs of strongly bound pesticides. Adsorbed pesticide reductions will generally be somewhat less than sediment reduction because of the enrichment of pesticides in the finer sediment fractions which are less effectively controlled by most SWCPs.

Pesticides which are lost primarily in the soluble phase of surface runoff can be controlled by runoff reducing practices. The extent of pesticide loss reduction should be proportional to the reduction in runoff volume. Possible exceptions to the above are conservation tillage systems where decreases associated with runoff reductions can be offset by increased availability of pesticides applied to sod or crop residue. Research results conflict on this issue with some showing significant pesticide loss reductions from conservation tillage systems while others have observed similar or even greater losses from conservation tillage versus conventional tillage. The degree of rainfall intensity appears to be the primary factor producing these conflicting results.

The persistence of a given pesticide is critical to the effectiveness of SWCPs in controlling its loss. Because most SWCPs function best for small to moderate size storm events and are often overwhelmed by the most major storm events, their long term effect is largely to retard the movement of pesticides from field to aquatic system. Hence, the degradation rate or soil leaching rate will greatly affect surface runoff and groundwater loadings.

For weakly to moderately adsorbed pesticides which are transported primarily in solution, there is generally an inherent trade-off between controlling surface runoff losses and increasing leaching through the soil profile to groundwaters. Management decisions to minimize overall environmental impacts should consider the persistence of the pesticide in relation to the rate of downward movement through the soil, the relative importance of and potential for use impairment by pesticides of neighboring surface and groundwater resources, depth to the water table, and adsorptive capacity of subsoils.

TABLE 9

Effects of Soil and Water Conservation Practices

Type of Practice	Effect on Runoff Volume	Effect on Soil Erosion	Effect on Delivery Ratio
Structural Practices			
Terraces			
level	-	-	-
graded	-	-	*
Subsurface drainage	0	-	-
Sediment Ponds	0	0	-
Nonstructural Practices			
Conservation Tillage			
chisel plow	-	-	0
ridge-plant	-	-	0
no-till	-	-	0
Contouring	-	-	0
Stripcropping	-	-	0
Grassed waterways	0	-	-
Diversions	0	-	*
Cover crops	-	-	0
Filter strips	0	0	-

1. "-" = Reduction, "+" = increase, "0" = Little or no effect.
"*" = Unknown, situation dependent or conflicting research results.
Information taken from Maas et. al. (77).

3.2 *PESTICIDE FORMULATIONS AND APPLICATION METHODS*

3.2.1 *Formulations*

As discussed earlier under pesticide transport modes the formulation can have a considerable effect on the loss by various transport routes. Among the most common formulations for herbicides and insecticides are wettable powders, dusts, concentrated emulsions, granules, liquid concentrates, soluble powders, aqueous solutions and flowable solids. Although the appropriate formulation is often dictated by the mode of action and the physical/chemical properties of the pesticides, where a choice exists, the following generalizations might aid selection:

1. Wettable powders and micro granules are considered the most susceptible for runoff losses (9);
2. Dusts, wettable powders and fine liquid sprays exhibit the greatest drift losses (30);
3. Aqueous solutions, liquids and liquid concentrates, especially when applied as fine sprays, show the greatest potential for volatile losses (17);
4. Formulations such as granules, pellets and emulsions generally reduce volatile and drift losses (8).

3.2.2 *Application Methods*

As shown earlier in the review of transport mechanisms, the application method can have a tremendous effect on pesticide loss by all transport routes. Matthews (111) has presented a detailed discussion of pesticide application methods emphasizing advantages, disadvantages, and specifications. Table 10 shows some of the major application options available for minimizing pesticide loss and indicates which transport routes are most affected. Only direct effects are included; i.e. an application technique which increases efficiency of use and thereby allows a lower application rate reduces the total amount of material available for transport but may not affect the percentage of applied material lost. For example, conversion from aerial to ground spraying: The direct effect is a reduction in drift losses, while the indirect effect might be that application rate is reduced, thus decreasing runoff and volatile losses.

3.2.2.1 Aerial Application

Indeed, as indicated earlier, the most effective single management practice for reducing pesticide field losses may be switching from aerial to ground application wherever possible. As noted by von Rumker et. al. (30) drift losses of any pesticide will be substantial with aerial spraying. In many cases, however, such conversion is not physically or economically feasible. Large fields where rapid pest outbreaks may occur or where application must be scheduled around other field operations may necessitate aerial spraying on the basis of timeliness. Crops which may require application at advanced growth stages often preclude the use of ground based equipment.

TABLE 10

Options for Reducing Pesticide Application Losses

Option	Effect on Runoff Losses	Effect on Drift Losses	Effect on Volatilization Losses
Mechanical			
ground vs. aerial application	0	-	0
controlled droplet applicators	0	-	-
computer controlled equipment	0	-	0
drift shielded ground sprayers	0	-	0
direct nozzles	0	-	0
ultra-low volume (ULV) equipment	-	+	+
electrostatic sprayers	0	-	-
Physical			
granules vs dust formulations	0	-	-
oil emulsion formulations	-	-	-
ultralow volume formulations	-	+	+
soil incorporated vs surface application	-	-	-
optimal choice of granular size	0	-	-
Management - timing			
spraying only on calm days	0	-	0
spraying late in day	0	0	-
using time release formulations	+	0	-
restrict application before precipitation	-	0	0
night spraying	0	-	-

"-" = Reduction, "+" = Increase, "0" = Little or no effect.

For situations where a conversion to ground application equipment is not practical, there are a variety of methods for increasing the efficiency of aerial application. One of the most important steps is to assure that the aircraft is providing an even distribution of pesticide to the target. This procedure, known as swath analysis, has recently begun using computer analysis of spray patterns to optimize the settings of application nozzles for maximum efficiency (91). Unlike ground-rig sprayers, uniform pesticide distribution patterns result from very uneven placement of nozzles on the spray boom because of air turbulence caused by the prop and wings of the aircraft itself. An increase in application efficiency of about 75% was observed for one test cited (91). Hydraulic nozzles on aircraft produce smaller drops than land machines because of the greater airspeed. This problem can be compensated to some extent by facing the jets backwards. The importance of highly even distribution becomes even more critical when using ultra-low volume application (92). Other methods for minimizing losses from aerial application include releasing pesticides as low above the target as possible as well as timing and formulation considerations. These latter include using granules, oil emulsion, or larger droplets as opposed to dusts and fine sprays and restricting applications to windless days when no heavy precipitation is forecast.

3.2.2.2 Ground Application

The pesticide application machine (applicator) must simiiltaneously disperse and aim the application to an extent that varies with mode of action, formulation and type of crop. It has been noted that dispersal and aiming necessarily conflict to some extent particularly when uniformity is considered an aspect of aiming. Very fine particles disperse better but their trajectory is more easily influenced by air movement (93). Thus, in at least a conceptual sense, all application equipment represents a compromise between these two functions. Put another way, most equipment advances in recent times have centered on reducing drift while still providing adequate and uniform dispersal. The measurement of drift itself is subject to large experimental error with the fall-out on sampling plates often poorly correlated with actual field and crop catchment (94).

Equipment which optimizes drop size can greatly reduce drift losses. Recent developments in rotating-disc sprayers have proven valuable for such controlled drop application. Drops of 500 um or greater will produce little drift, and except in extremely dry conditions, drop size can be reduced to 100 or 200 um with minimal drift. As important as the median drop size is the ability to produce drops within a narrow size range, reducing the output of small drops. One recently developed machine reduces drift by transmitting the spray horizonally at such a height that the horizontal component of drop movement has ceased before the crop is reached so that drops are falling vertically under calm conditions (94). The importance of drop size is illustrated by the work of Ware et. al. (95) who found that drift was twice as large for a ground based mist blower applying 100 um drops as from an aerial application with 140 um drops.

Equipment and formulations which use spray thickeners have also been shown to reduce drift. These are usually water-pesticide or oil-pesticide emulsions. The high viscosity reduces small drop formation in the nozzle (93). Oil emulsions can also reduce volatilization losses. Recent studies with a controlled drop applicator using a soybean oil carrier showed that with a median drop size of about 300 um. only 0.64 to 1.07% of the total volume was released as droplets of less than 100 mm diameter (158). Electrostatic sprayers have recently added a method for using small (30-50u) easily dispersible drop sizes while minimizing drift. A negative charge is added to the spray droplet by a small electrode charging cap embedded near each nozzle tip. The negatively charged drop is attached to the positively grounded plant (93, 96). Preliminary studies indicate less drift and better foliar coverage for insecticides than with conventional spraying equipment (96). A variation of the electrostatic sprayer is the recirculating sprayer in which droplets which are not deposited on plant or soil surfaces are electrostatically recaptured by the sprayer. Machinery costs are high at this time, however, this innovation may prove very useful for ultra-low volume application. At the present time ULV techniques are becoming more popular because of reduced carrier expenses and because more acreage can be treated with fewer refilling stops (92): However, the potential for drift losses is correspondingly increased by the small droplet sizes employed. Wick applicators are a recent innovation for applying contact herbicides with maximum efficiency. The herbicide-saturated rope wick is drawn through the field just above the level of the crop.

3.2.2.3 Management - Timing

Considerations for management decisions which can reduce pesticide losses are shown in Table 10. These can be grouped by the way they affect various pesticide transport mechanisms.

3.2.3 *Reducing drift losses*

As discussed previously the major factor influencing drift losses are application method, pesticide formulation and wind velocity. Investigations by several researchers have shown wind velocity to be the most important factor affecting drift losses (30, 8, 53) with drift loss ranging from 0 to 50 percent depending on wind velocity. On this basis the BMP for reducing drift is to restrict applications to windless days or to periods of the day (for example: early morning, early evening or night) when wind velocity is minimized. Spraying in windspeeds above 5 mi/hr should be avoided in all cases. A recent statistically based study has shown that night spraying would actually be the most effective means of minimizing both drift and volatilization because of reduced windspeeds and evaporation potential (112).

3.2.3.1 Reducing volatilization losses

Volatilization losses increase with pesticide volatility, air temperature, soil temperature, and wind velocity and decrease in humidity. Losses of triazines and organochlorines are particularly dependent on soil and air temperatures (20, 21, 23,152). Thus, it can be concluded that in terms of timing decisions the BMPs for reducing volatile losses involve applying pesticides on windless, humid and cool days to the extent possible. Spraying should also be done late in the day or at night to reduce volatile losses and increase the time of contact between plant or insect and pesticide. This is particularly important for pesticides such as organophosphorus and organochlorine insecticides where the half-life on foliage or soil may be on the order of a few hours or less under hot, dry conditions (8).

3.2.3.2 Reducing runoff losses

For all the pesticide classes previously discussed in Section II it is apparent that by far the greatest runoff losses occur when a significant runoff event occurs shortly after application. The shorter the interval between application and runoff, the greater the pesticide runoff losses (9). For this reason, in terms of application timing options, avoiding application when the probability of significant precipitation is high is a BMP for reducing runoff losses. Careful attention should be paid to local weather forcasts in application decision making.

Chapter 4

INTEGRATED PEST MANAGEMENT (IPM) SYSTEMS

4.0.4 *Basic Principles*

Some of the individual non-chemical options for reducing pesticide usage are shown in Table 11. These, together with use of pesticides and the various application techniques, form the basis of integrated pest management. IPM has been defined as an interdisciplinary approach to pest control incorporating the judicious application of ecological principles, management techniques, and biological and chemical methods to maintain pest populations at tolerable levels (98).

After several decades of almost exclusive reliance on chemical strategies for controlling agricultural pests, IPM has received wide support in recent years. This support has increased because of the high cost of pesticides and a perception that the negative effects of chemical pesticide reliance have continued to magnify. These apparent negative effects include increasing pest resistance which continually reduce pesticide effectiveness; emergence of new pests due to disruption of ecological controls; extensive contamination of water, air, and soils; widespread human health hazards (over 40,000 reported cases of pesticide poisoning in 1980) (98); and increasing pesticide costs. This growing support for IPM is perhaps best exemplified by the 1979 Presidential Directive to federal agencies to "modify as soon as possible existing pest management, research and control education programs to support and adopt IPM strategies" (99). At the farm level many farmers receive most of their information on pesticide selection and use from the local distributor whose livelihood is tied to the quantity of pesticides sold (6, 3, 101). Rapid progress has been made in addressing obstacles to the adoption of a sound ecological approach to pest control. An excellent summary of federal and state actions in recent years to encourage IPM had been published by Allen and Bath (100).

One of the basic tenants of IPM is that optimal pest control systems are highly situation-specific and depend on extensive knowledge of the ecology of the system of interest. Several excellent books have recently been published which give detailed explanations of the IPM tools shown in

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TABLE 11

Major Components of Integrated Systems for Reducing Pesticide Usage

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a. more efficient application methods (see Table 10)
b. pesticide application based on economic thresholds
c. use of resistant crop strains
d. timing of field operations - planting, cultivating harvesting
e. researching crop-pest ecosystem
f. scouting
g. use of biological controls
    1) introduction of natural enemies
    2) preservation of predator habitats
    3) release of sterilized male insects
h. use of pheromones
    1) for monitoring populations
    2) for mass trapping
    3) for disrupting mating behavior of pests
m. crop rotation
n. destruction of pest breeding, refuge and overwintering sites
o. use of "trap" crops
p. habitat diversification
q. use of botanicals

Table 11. Among these are An Introduction to Integrated Pest Management, Flint and van den Bosch (6); The least is Best Pesticide Strategy, Goldstein (101); New Technology of Pest Control, Huffaker (102); Plant Protection: An Integrated Interdisciplinary Approach, Sill (103); Integrated Pest Management, Apple and Smith (109); and Integrated Pest Management: Rationale, Potential, Needs and Implementation, Glass (104). The remainder of this section is devoted to describing briefly some IPM concepts and to highlighting some recent information which has been published subsequent to the above-noted references. Case studies involving specific IPM systems will be included as part of major crop pest control system discussions and recommendations in Section IV.

Flint and van den Bosch (6) suggest the general guidelines for setting up IPM programs which are summarized below.

1. Understand the biology of the crop, and how it is influenced by the surrounding ecosystem. Important considerations include the type of life cycle (annual, biennial, perennial); growth initiation factors (temperature, moisture, photoperiod); how the crop plant responds to stress such as drought, nutrient deficiencies and temperature; and how environmental conditions affect growth rates and cycles.

2. Identify the key pests; know their biology; recognize the kind of damage they inflict; and initiate studies on their economic status. Key pests are organisms which cause significant yield or quality reductions regularly in the absence of pest management action and usually there are only one or two key pests in a given managed resource system.

3. Identify the key environmental factors that impinge (favorably or unfavorably) upon pest and potential pest species in the system. These are factors which limit the survival, development and reproduction of key pests and usually include natural enemies (parasites, predators and pathogens), availability of food sources, temperatures, water availability, photoperiod, shelter and overwintering sites.

4. Consider concepts, methods and materials that individually and in combination will help suppress permanently or restrain pest species. Examples include introducing and establishing new natural enemies to the system or permanently altering the pests' physical environment to reduce reproduction and/or survival.

5. Structure IPM programs so they will have the flexibility needed to adjust to ecosystem changes. Variations in pest situations may be observed between neighboring fields and between years.

6. Anticipate unforseen developments; expect setbacks; move with caution, and remain aware of the ecosystem complexity.

7. Seek the weak links in the key pest life cycle and narrowly direct control practices at these weak links avoiding broad ecosystem impacts. This includes applying control when the pest is more vulnerable with tools that include pesticides or natural enemies.

8. Whenever possible use methods which preserve, complement and augment biotic and physical mortality factors of the pest. Examples include providing supplemental food sources for parasites and predators,

adjusting planting times, and properly timing the use of selective pesticides.

9. Whenever feasible, attempt to diversify the ecosystem. Managed ecosystems have much less diversity in terms of genetics, age, species and physical characteristics than natural ecosystems. While this is generally necessary for maximizing production efficiency, it generally decreases the system's ability to resist new stresses. Small changes to increase diversity such as the addition of an alternative food source shelter area, or pest host can make the difference between effective and ineffective pest control (6, 102, 103).

4.0.5 *Monitoring*

Together, the above guidelines provide a strong conceptual framework for how any IPM system should be designed. It is clear from the above discussion that scouting and monitoring (surveillance) are perhaps the most important ingredients of an IPM system. All decisions and actions for pest control should be based on accurate timely information on pest dynamics. Scouting or monitoring involves sample collection in the field to determine pest levels and life cycle stages. Among the sampling schemes used are random sampling (4 or more counts of pest numbers and/or damage per field); point sampling (detailed monitoring of pests, natural enemies and crop maturity in one area per field); traps (light traps, sticky traps, pheromone attractant traps (106)) which usually only determine pest presence rather than density; and sequential sampling, a low cost method using economic thresholds to determine whether further sampling is needed (6). It should be noted that economic thresholds are a very dynamic quantity which respond to factors both internal and external to the agroecosystem.

In practice, scouting or field monitoring for weeds have proven easier than for insects because weeds are less transient. Two or three detailed scoutings and mappings per season have generally been found to be sufficient (105).

4.0.6 *Control Action Thresholds*

The basic reason for determining thresholds is to differentiate the mere presence or innocuous levels of a pest from densities which will cause significant damage. In many cases a crop can tolerate large numbers of insects or considerable weed competition without significant yield losses. The principal of economic injury levels is based on the concept that pest control is not justified until crop injury reaches the level where the cost of control is less than the cost the farmer would incur if control action were not taken. Recent IPM models utilize this concept by determining optimal pest management systems on the basis of profits to the producer rather than on maximization of yields (130,131). In fact, most IPM studies have found that maximum net returns are realized from management alternatives which do not maximize crop yield but rather optimize between pest-induced yield reductions and reductions in pesticide costs (127,130,131,141).

As noted earlier, the interaction between the growth stages of crop and pest species has a great effect on the economic injury level of a crop. Most pests are able to cause economic injury only during limited periods of the plant or pest life cycle. An example is the tobacco budworm which causes damage by feeding on tobacco leaf buds. However, by mid-summer all the leaves have emerged from their buds so that the budworm regardless of density level cannot cause economic damage for the remainder of the plants' life cycle. Natural enemies also have an effect on economic injury levels. Untreated cotton in California has an economic threshold of 15 first or second instar bollworm larvae per 100 plants. In insecticide treated fields this threshold drops to 8 larvae per 100 because of destruction of natural bollworm enemies (6).

4.0.7 *Biological Controls*

1. natural enemies.

   The role of natural enemies has already been mentioned. Control by natural enemies is generally cheap, effective, permanent and nondisruptive, and thus should be a paramount consideration in pest control strategies. Unfortunately, it is also the factor most likely to be disrupted by the employment of other control tactics particularly chemical pesticide use.

2. host resistance.

   This involves the genetic manipulation or selection of plant varieties which have pest resistant qualities. Resistance may be due to physiological factors (e.g. toxic compound produced by plant), morphological factors (e.g. a cuticle which is too thick for penetration by the pest) or increased tolerance in which case pests continue to feed on the host but damage remains below economic injury thresholds.

3. autocidal control.

These are tactics which cause the pest to contribute to the reduction of its own population. The most common tactic is to release sterile males which are equally competitive with wild varieties thus reducing reproduction success. Theoretically this technique can reduce a given pest population almost to zero; however this assumes that the release area is geographically isolated and that sterilized males are easily reared and remain sexually competitive (6). Such repetitive releases are also quite expensive.

4.0.8 *Cultural Controls*

Cultural controls are modifications of management practices that make the environment more unfavorable for survival, movement and reproduction of pests. Cultural tactics include timing of planting and harvesting, timing of other field operations, field sanitation, tillage, trap crops, cultivating, habitat diversification, and crop rotation.

Crop planting can often be timed to give the crop a competitive advantage over the pest. This has proven effective for both insects and weeds. Harvesting practices such as early harvest before occurrence of economically injurious levels of pests which feed directly on the marketable portion of the plant have proven effective for a wide variety of pests including sugar cane borer, sweet potato weevil, potato tuberworm and cabbage looper (6). Tillage practices destroy both insect and weed pests by mechanical injury. Trap crops have proven especially effective in cotton growing areas where a small portion of the field can be planted in an early fruiting crop which attracts the majority of pests. This area can then be sprayed with very high killing efficiency while not impacting natural enemies in the rest of the area. Crop rotation has long been shown to reduce pest problems especially for pests which cannot survive over one or two seasons without host contact.

A majority of the IPM control tactics discussed in this section have either implicitly or explicitly referred to insect as opposed to weed control. The reason is that insect control IPM programs have been under development longer and have a considerably higher knowledge base than weed IPM programs which are still in their relative infancy. However, several concepts, theories and techniques for non-chemical weed control systems are developing and deserve special mention. Several of the IPM tactics discussed above are used for weed control as well as insect control. These include tillage, crop rotations, and monitoring. In addition, nonchemical weed control tactics have included mulching (on intensively grown crops) and use of natural weed enemies (parasites, pathogens, and especially insects) (107). Recent work has focused on weed habitat modification procedures that disturb weed growth or change competitive patterns. Such measures include optimizing row spacings, adjusting time of planting and fertilization patterns to give the crop the maximum competitive advantage (105). There is also extensive evidence that using weed-free seed is a cost-effective BMP for weed control (107).

4.0.9 *Evaluating IPM Programs*

Evaluating the success of IPM has proven to be a difficult task. Pest problems vary widely on an annual basis as a function of climatic and other environmental conditions. This limits the reliability of 'before and after' evaluation. Even the traditional approach of comparing IPM participants with non-program cooperators is of limited use because of the farm to farm variation of pest dynamics and the influence of adjacent pest control systems on each other. In several areas where long term comparisons have been attempted the control group has become smaller with time, to the point where all producers of a given commodity and geographic area have adopted some level of IPM (108). The methodology being used by Boutwell and Smith (108) involves the correlation of the percentage of recommended IPM tactics being used by individual producers with their crop yields and net returns.

Very little evaluation of IPM programs has been done in regard to their effect on water quality. The assumption generally made is that the reduction in field loss of pesticides will be proportional to the reduction in application rate. This assumption can be in error in either direction depending on the pesticide, soil type and other field characteristics.

4.1 *SUBSTITUTION OF MORE SELECTIVE OR LESS PERSISTENT PESTICIDES*

The fourth major group of techniques, substitution of more selective/less persistent pesticides, also reduces aquatic pollution by reducing the amount that can reach the aquatic system. These may also augment the effects of the preceding three groups of BMPs. SWCPs can increase the residence times of certain pesticide classes on the field before they are washed off to aquatic systems. Less persistent pesticides sometimes have the agronomic disadvantage of requiring more frequent application. If less persistent pesticides are substituted, then SWCPs can be a more effective means of reducing pesticide runoff impacts on aquatic systems. The same principal applies for reducing the impact of drift and volatilization losses by modifying application techniques. Although little is known about the atmospheric residence time of volatilized pesticides, it is clear that effective redeposition fluxes will be lower for more atmospherically degradable materials. The use of highly selective pesticides plays a vital role in the effectiveness of IPM systems. Selective pesticides which minimize disruption of natural enemy dynamics ultimately increase the efficiency of pest control on a long-term basis.

The greatest advance in the selectivity of pesticides has come in the area of natural and synthetic pyrethroid development. Natural pyrethroids represent the ideal insecticide because of their selective action against a single insect species, their lack of toxicity to humans, their rapid degradation, their high efficacy (low application rates), and their low potential for promoting resistance among pest species. However, the identification, extraction and purification of biologically active pyrethroid isomers is very costly and has only been accomplished for a few insect species. Unfortunately, there is limited economic incentive for research or development because the high selectivity limits the market to a single pest.

Synthetic pyrethroids basically are chemical analogs of natural pyrethroids that work in the same manner as natural pyrethroids. They are less expensive to produce and in some cases are effective on more than one group of related pests. Synthetic pyrethroids have practically revolutionized insect control in cotton, replacing toxaphene and organophosphorus insecticides on the majority of insecticide treated cotton acreage (63). In fact, the cotton acreage treated with toxaphene has declined by 81 percent since 1976. Synthetic pyrethroid usage has also increased dramatically on soybeans, and is now used more extensively than any other insecticide on this crop. A recent USDA report indicated that substitution of synthetic pyrethroids has resulted in a significant decrease in overall U.S. insecticide demand

(71). This is due to a combination of their low application rates, infrequent need for application, and particularly because their light damage to beneficial insects and predators reduces overall insecticide needs. One drawback from the standpoint of water quality impacts is the fact that the most commonly used synthetic pyrethroids are very highly toxic to fish with 96hr LC(50) values in the low or sub part-per billion range (113,153).

Chapter 5

PESTICIDE BMP SYSTEMS BY CROP AND REGION

As noted earlier the most effective pest management strategies for optimizing agricultural production and water quality concerns are highly situation specific. In fact, pest population and pesticide transport dynamics vary year to year, farm to farm and even between fields. For this reason flexibility must be built into any pest management program to maximize effectiveness. With these concepts in mind this section examines case studies of pest management systems for major crops and regions and attempts to integrate these case studies with other information on pest management practices for reducing water quality impacts. The results are general guidelines for pest management in major crops and areas with an added emphasis on the reduction of pesticide losses to aquatic systems. Some regions of the U.S. have important economic crops which are not considered major crops on a national scale. BMP systems for these locally important crops will also be mentioned where information is available. Unfortunately, as will become apparent in the following discussions, many BMP systems have been designed for one class of pest (i.e. insects, weeds, nematodes) without adequate consideration of the overall system. This results in recommendations which do not take into consideration other production necessities, or in the worst cases, recommendations which conflict. In each example an attempt is made to estimate the reductions in pesticide inputs to aquatic systems possible for various combinations of BMP systems relative to traditional production practices. In a few cases, these estimates are based on quantitative research results. However, for most cases these estimates are based at least partially on an intuitive and conceptual consideration of the pesticide loss reductions possible through the combination of SWCPs, application improvements and IPM.

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5.1 *PESTICIDE BMPS FOR CORN*

Corn is the largest single cash crop in the United States. In 1982, almost 82 million acres were planted (63). Of this acreage about 95 percent was treated with herbicides and about 37 percent with insecticides. In spite of this vast acreage and the large associated pesticide use, corn has lagged behind several other major crops in the development of biological and other nonchemical pest control strategies. Both herbicide and insecticide treatments to corn are generally made very early in the growing season when the potential for erosion and runoff losses are great due to the lack of vegetative cover and high precipitation probability. In addition a larger percentage of corn is grown on land classified as highly erosive by the 1977 National Resources Inventory than any other crop except tobacco (161). Hence, at a national level, the application of SWCPs to corn acreage can make a significant contribution to reducing impacts of pesticides on aquatic systems.

Most pesticide application to corn is made by ground-based equipment and much of this material is in granular form. Thus, the potential for reducing pesticide inputs to aquatic systems through improvements in application techniques is less for corn than for some other major crops.

5.1.1 *Insecticide Reduction through IPM*

5.1.1.1 **Scouting**

Current insect control practices in corn are very dependent on chemical insecticides, primarily carbofuran and various organophosphorus compounds, with other controls usually subordinate. Replacement of prophylactic soil treatments for corn rootworms with better scouting programs is one way that insecticide use can be reduced. It appears that extensive treatment for corn rootworm takes place in fields with little or no potential for rootworm damage. A four-county Illinois study found that in 1974 and 1975, 19 and 11 percent respectively of corn acreage actually needed insecticide treatment, while in fact, 67 and 57 percent respectively were treated (115). A three-year study in the Midwest showed that only 9 percent of corn fields even contained wireworms, and only 1.2 percent actually had wireworm damage (114). This illustrates the potential for reducing corn insecticide use through the substitution of appropriate scouting and monitoring accompanied by IPM education programs.

5.1.1.2 Crop Rotation

It has been known for some time that the most effective management practice for controlling corn insect pests is crop rotation. The largest insect pests of corn are the various species of corn rootworm. The corn rootworm is unable to survive over a year when another crop is planted, and thus corn rootworm populations are dramatically reduced by rotations that skip corn on consecutive years. In the short-term, the practice often suffers some economic disadvantage compared to rotations with successive corn planting. However, in many cases alternating corn with some other annual row crop such as soybeans, grain sorghums, forage sorghams, or alfalfa at least partially and sometimes completely compensates for the loss of the corn rotation because of reduced fertilizer applications, increased yields during corn growing years and decreased insect problems. For farmers heavily reliant on corn production on a majority of fields, Luckman (115) proposes a compromise which takes advantage of both scouting and crop rotation. The concept is to monitor corn fields at the end of the growing season for rootworm beetle population. Fields with high infestation levels should be rotated to another crop the following season while fields with lesser populations may be replanted to corn the following spring. An extensive economic analysis of corn cropping in the Midwest by Lazarus and Swanson (154) produces a similar recommendation. Other non-chemical management tactics for corn insect control involve adjusting planting and harvesting dates to minimize damage or substitution of of insect-resistant crop strains.

As presently practiced insecticide usage is only approximately 16 percent higher in no-till as compared with conventionally tilled corn (78). This increase is reflected in both higher application rates and increased acreage of treatment. The increased insecticide requirement is a result of the lack of tillage to destroy or disrupt soil insects and resistant weeds. The surface residue may also result in cool, damp, early season soil conditions which increase seedling susceptibility to insect damage (117). Thus, crop rotation becomes even more important for insect control in reduced-tillage systems. The effect of reduced tillage on runoff losses of applied insecticides (carbofuran, OPs) is unclear from the research conducted to date. Table 12 summarizes the estimates of pesticide loss reductions from various BMPs and BMP combinations for corn. These estimates are made at the field level as compared with a hypothetical field utilizing conventional, traditional or typical cropping practices realizing that these practices may vary considerably between geographic regions.

5.1.2 *Possible Herbicide Reductions through IPM*

IPM programs for weed control in corn are not well developed. Again, crop rotations somewhat reduce herbicide requirements because some perennial weeds are more easily controlled by competition or different herbicides in other crops.

The growing use of no-till and other reduced tillage systems for corn has important implications for both herbicide and insecticide application and loss. Although Hanthorn and Duffy (78) have shown that herbicide usage is not significantly greater for reduced tillage systems, the potential for weed problems from the reduction in cultivation does not lend optimism for significantly reducing herbicide usage in reduced tillage systems (116). Furthermore, there is conflicting evidence on whether reduced tillage systems actually reduce the percentage of applied herbicide lost in runoff.

TABLE 12

Estimates of Potential Reductions in Field Losses of Pesticides for Corn Compared to a Conventionally and/or Traditionally Cropped Field (1)

Management Practice	Transport Route(s) Affected	Range of Pesticide Loss Reduction (Percent)(2)
SWCPs	SR and/or SL(#)	
Terracing	SR and/or SL	40-75AB (25*)
Contouring	SR and/or SL	15-55AB (20*)
No-till	SR and/or SL	-10 - +40B 60 - +10A (10*)
Other Reduced Tillage	SR and/or SL	-10 - +60B -40 - +20A (15*)
Grassed Waterways	SR	-10-20AB
Sediment Basins	SR	0-10AB
Filter Strips	SR	0-10AB
Cover Crops	SR and/or SL	0-20B(3)
Optimal Application Techniques (4)	All Routes $	10-20 20-40B
Nonchemical Methods	All Routes	
Adequate Monitoring	All Routes	40-65A
Crop Rotations	All Routes	40-70A 10-30B

* Refers to estimated increases in movement through soil profile.

# SR = Surface Runoff
SL = Soil Leaching
$ Particularly drift and volatilization

1. The hypothetical field used as the basis for comparison utilizes the following management system: a) Conventional tillage without other SWCPs. b) Ground application with timing based only on field operation convenience. c) Little or no pest monitoring; spraying on prescribed schedule. d) Corn grown in 3 out of 4 years.

2. Assumes field loss reductions are proportional to application rate reductions. A = insecticides (carbofuran and O.P.s) B = Herbicides (Triazine,

Alachlor, Butylate, Paraquat) Ranges allow for variation in climate, slope, soils and types of pesticides used. Ranges for No-till and Reduced-till are derived from a combination of increased application rates and decreased runoff losses.

3. Cover crops only will affect runoff and leaching losses for pesticides persistent enough to be available over the non-growing season. In the case of pesticides used on corn only the triazine and anilide herbicides will generally meet this criteria.

4. Defined here for corn as ground application using optimal droplet or granular size ranges, with spraying restricted to calm periods in late afternoon or evening.

5.2 *PESTICIDE BMPS FOR SOYBEANS*

Annual soybean acreage has increased steadily during the past decade to where in 1982 it was only slightly less than total corn acreage (81.9 million vs 72.2 million acres) (63). Of the total acreage, 93 percent receives herbicide treatment but only 12 percent is treated for insects. The major herbicides used are metribuzin (triazine), trifluralin (dinitroaniline) and alachlor. Primary insecticides are carbaryl, various OPs, synthetic pyrethroids and toxaphene. Definitive research has shown that all three of the above herbicides are lost almost entirely in the dissolved phase of runoff (8). Of the insecticides, only toxaphene is lost primarily in the sediment bound phase. Thus, reductions in herbicide losses should be roughly proportional to runoff reductions for SWCPs, again with the exception of surface residue effects that may result from reduced tillage.

Soybean pest problems vary considerably between regions. The main soybean producing regions of the U.S. are the Corn Belt, the South and the Southeast. Traditional production has been confined to the Corn Belt and North Central regions and at the present time there are no major soybeans insect pests in these regions (118). Much of the Corn Belt is also relatively free of serious weed infestations although some herbicidal control is needed on most fields (119). In the Mid-South and Southeast, on the other hand, where production acreage has increased dramatically in recent years, soybeans are subject to attack by a large complex of insect pests (120,121). Weeds are also a very difficult problem often requiring multiple applications of both pre- and post-emergence herbicides (122).

5.2.1 *Possible Reduction in Insecticide Use Through IPM.*

The use of IPM systems for insect control in soybeans has not been given much attention until recently as production increased and expanded into new areas. However, several extensive studies have recently been conducted (118,120,121,123,124). The largest effort has been the NSF/EPA/USDA "Integrated Pest Management Project on the Principles, Strategies, and Tactics of Pest Population Regulaton and Control in Major Crop Ecosystems" (123).

The most common IPM tactics for soybean include: 1) adequate monitoring and scouting, 2) optimal planting dates, 3) use of natural control agents, 4) Resistant varieties, 5) trap crops, 6) selective use of insecticides, and 7)treatments based on economic injury levels.

In relation to economic injury levels, the soybean has a remarkable ability to compensate for injury by insects without loss of yield or quality (118). Hence, in its traditional production regions, control by natural agents has generally been sufficient.

In contrast to the Corn Belt, the new production regions of the south-central and southeast U.S. have serious potential for insect pest problems as insects become adapted to the new ecological niches available in soybean cropping. The major challenge is to prevent the escalation of secondary pests, the development of resistance and the loss of natural predator controls, all of which are fostered by the improper use of chemical insecticides (121).

In North Carolina and some other southeast states the corn earworm, Heliothis zea, has historically been the major soybean insect pest (120). Non-chemical control methods emphasize early planting so that a plant canopy is formed before the flight of second generation moths. Related to this are the use of narrow rows, plant varieties which form an earlier canopy and other tactics to insure adequate crop health. The earworm may be controlled by low rates of carbaryl, based on larval populations to minimize disturbance of natural biological control complexes.

The velvetbean caterpillar is the most important soybean pest in Florida and Southern Texas. Wilkerson et. al. (124) describe a spraying decision model based on insect scouting information, crop growth stage, and economic threshold which effectively minimizes the amount of pesticide application for this pest.

In much of the rest of the South, various species of stinkbugs are the major pests. Stinkbugs feed directly on soybean pods and can cause considerable economic damage.

The most effective non-chemical control technique has been the use of trap crops, generally small areas (less than 5% of the total), planted to varieties that mature one to two weeks before the remainder of the crop. The early maturing variety attracts the vast majority of stinkbugs as the pods begin to fill and can be very efficiently sprayed with little predator damage and minimal selective pressure (121).

5.2.2 *Possible Reduction in Herbicide Use*

Annual weeds, particularly giant foxtail, are the major weed problem in the Corn Belt. These can be controlled to a large extent by crop rotation (119). Extensive cultivation is also considered a major factor in reducing herbicide requirements on soybeans. Hanthorn and Duffy (78), however, found that herbicide usage was not significantly greater for most reduced tillage systems than for conventional tillage (Table 9). No-till systems used significantly more herbicides only in the Midwest. Herbicide treatment in the Corn Belt generally consists of using preplanting and pre-emergence herbicides. No-till systems often require post-emergence herbicides as well. Present efforts to reduce herbicide use focus on precise calculation of required rates on the basis of soil organic content and pH as well as using spot applications within fields (119).

Soybeans grown in the South-Central and Southeast regions are subject to severe annual and perennial weed infestations due to favorable climatic conditions (121). Post-emergence as well as pre-plant and pre-emergence herbicides are often required to maximize return. As in the Corn Belt, crop rotation and precise application rates are BMPs. Early planting, in addition to reducing corn earworm problems, also reduces weed problems by providing an early crop canopy. It is clear that much more research on non-chemical means of soybean weed control is needed in the South.

5.3 *PESTICIDE BMPS FOR COTTON*

Cotton has more proven potential than any other major U.S. crop for achieving reductions in pesticide usage and loss to aquatic systems through IPM, improved application efficiency, and pesticide substitution. The percentage of cotton acreage treated with herbicides rose from 82 to 97 percent between 1971 and 1982. However, actual amount of herbicides used decreased by more than 10 percent during the same period (63). A wide variety of herbicides are used, but trifluralin and fluorometuron are the most predominant.

Insecticide use on cotton has been reduced substantially since 1976. The percent of acreage treated with insecticides has decreased from 60 to 36 percent in this period and the amount by weight has dropped by almost three-fourths (from 64.1 to 16.9 million pounds) (63). The majority of this decrease can be attributed to the replacement of routine methylparathion and toxaphene treatment by IPM and synthetic pyrethroids in addition to the adoption of early maturing varieties to avoid late season pest problems.

Table 13 summarizes estimates of potential pesticide loss reductions from various BMPs and BMP systems at a field level as compared with a hypothetical field utilizing cropping practices which were typical until the late 1970s. The uncertainty of the estimates is a function of the rapid transitions in production method described above coupled with the variance among regions and seasons. SWCPs in particular are not as effective on cotton as with corn and soybeans because much cotton is grown on relatively flat land with little or no water erosion problems (161).

Considerable potential exists in the case of cotton for reducing aquatic pesticide inputs from drift because a high percentage of treatment is made by aerial equipment.

TABLE 13

Estimates of Potential Reductions in Field Losses of Pesticides for Cotton Compared to a Conventionally and/or Traditionally Cropped Field (1)

	Transport Route(s)	Range of Pesticide Loss Reduction (Percent) (2)
SWCPs		
Terracing	SR and SL#	0-(20*)
Contouring	SR and SL	0-(20*)
Reduced Tillage	SR and SL	-40 - +20 AB
Grassed Waterways	SR and SL	0-10AB
Sediment Basins	SR	0-10AB
Filter Strips	SR	0-10AB
Cover Crops	SR and SL	0-10A -20 - +10B
Optimal Application Techniques (3)	All Routes($)	40-80A 30-60B
Nonchemical Methods	All Routes	
Scouting Economic Thresholds	All Routes	40-65A 0-30B
Crop Rotations	All Routes	0-20A 10-30B
Pest Resistant Varieties	All Routes	0-60A 0-30B
Alternative Pesticides	All Routes	60-95A 0-20B

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* Refers to estimated increases in movement through soil profile.
# SR = Surface Runoff
SL = Soil Leaching
$ Particularly drift and volatilization

1. The hypothetical traditionally cropped comparison field utilizes the following management system:
   a) Conventional tillage without other SWCPs.
   b) Aerial application of all pesticide with timing based only on field operation convenience.
   c) Ten insecticide treatments annually with a total application of 12 kg/ha based on prescribed schedule.
   d) Cotton grown in 3 out of 4 years.
   e) Long season cotton varieties.

2. Assumes field loss reductions are proportional to application rate reductions.

A = insecticide (toxaphene, methylparathion, synthetic pyrethroids).
B = Herbicides (trifluralin, fluometron).
Ranges allow for variation in production region, climate, slope and soils.

3. Defined for cotton as ground application using optimal droplet or granular size ranges with spraying restricted to calm periods in late afternoon or at night when precipitation is not imminent.

5.3.1 *Potential Insecticide Reductions Through IPM*

It is widely recognized that further reductions in insecticide use on cotton will occur as IPM programs expand and their combined effects stabilize and reduce the pest status of various species. This should also lessen selective pressures towards producing insecticide-resistance in pest species (127).

A number of studies on the substitution of IPM and synthetic pyrethroids for the hazardous and persistent toxaphene suggest that this pesticide can be eliminated from cotton production systems entirely (8, 127, 128). As a result of the cotton IPM effort spearheaded by the NSF/EPA/USDA IPM project, functional integrated systems have been developed for all major cotton producing regions of the U.S. In Arkansas, implementation of the suggested IPM system resulted in an 80 percent reduction in the number of sprayings for the bollworm (129). California IPM projects through emphasis on scouting and economic thresholds have dramatically reduced insecticide needs in this important production region without reducing yields or profits (128,130). IPM efforts in Texas have emphasized using short season cotton to eliminate late season insect problems and reducing spraying for flea hoppers (127,129,131). In a Mississippi study insecticide costs were cut in half simply by using a cotton crop model to key insecticide treatments to economic thresholds (128).

It is currently very difficult to assess what further reductions in cotton insecticide use are presently feasible because of the rapid transition presently underway. The current trend in cotton production involves pesticide substitution by materials that require lower application rates and have less adverse effect on natural control agents, a reduction in aerial spraying, and use of pest resistant crop varieties. However, given the short time during which these advances have been under development, further developments are nearly certain.

5.3.2 *Potential Herbicide Reductions*

Almost no attention has been given to weed IPM systems for cotton in the published literature. The focus of concern has understandably been on developing insect IPM programs. The heaviest cotton herbicide use is in the Mid-South growing region where hot, humid weather contributes to prolific weed growth. Reductions in herbicide use have come about primarily through improved application efficiency, more effective herbicides, crop rotation (primarily with soybean (115)), and increased scouting activity. Additional improvements in these have the potential to somewhat further reduce herbicide usage without adversely affecting economic returns.

5.4 *TOBACCO*

Herbicides and insecticide use has steadily increased over the past decade on tobacco lands. Treatment reached 71 percent (herbicides) and 85 percent (insecticides) of total acreage in 1982 (63). The tobacco IPM program for North Carolina developed by Rabb et. al. (132) addresses the two major N.C. tobacco insect pests, The tobacco budworm and the tobacco hornworm; nematodes, particularly the root knot nematodes; and the three common plant pathogens, tobacco mosaic virus, bacterial wilt and "black shank", a fungal disease.

Four natural predators, the stilt bug, paper wasps, a parasitic wasp and a parasitic tachnid fly have proven effective for control of the hornworm and budworm such that there is only occasional need for an insecticide application. Cultural controls for nematodes and pathogens include crop rotation and use of resistant varieties. Field sanitation including rapid post-harvest removal of crop stubble is especially important for control of all three pest classes. This is one area where considerable improvement is still needed although post harvest sanitation has become standard recommended practice. Significant reductions in insecticide, nematocides and multipurpose pathogen control chemicals should be possible as these systems are used more widely in tobacco production.

Tobacco lands are very significant from a water quality perspective. The sensitivity of the crop to excess soil moisture means that surface drainage systems are generally required which increases the delivery ratio of applied pesticides to nearby aquatic systems. Also, a large percentage of tobacco lands are classified as highly erosive. Hence, tobacco acreage represents a small but potentially intense pesticide source.

5.5 *DECIDUOUS TREE FRUITS*

The major deciduous tree fruits in the U.S. include apples, peaches, pears, cherries, and plums. Of these, apples are by far the largest and most widespread crop and have received the most attention in IPM program development.

Nearly 12 million pounds of pesticides were used on apples in the U.S. in 1978 (98) ranking this crop in the top six in pesticide use. Of this amount over 7 million pounds were fungicides. Research efforts (133,134,135,136) in several areas of the country have developed IPM technology for apples and other deciduous tree fruits which should reduce pesticide use by 50 to 80 percent, depending on region and the current level of IPM practiced. Excessive and often unnecessary state and federal "cosmetic" standards for grading and marketing fruit continue to pose a major barrier to the adoption of IPM and subsequent pesticide use reduction (6,137).

5.6 *OTHER CROPS WITH HIGH PESTICIDE USAGE*

IPM programs have been developed or are under development for many other crops of national or regional significance including alfalfa, potatoes, citrus and peanuts. Implementation of these programs can complement the potential pesticide reductions described thus far. Regionally, these may be of even greater importance since they may represent the major crop and source of pesticide contamination for a region.

An example is the development of IPM programs for potatoes which are a dominant crop in areas of Maine, Colorado, and Idaho. Research in each of these areas (138,139,140) shows that fungus and insect problems and the associated need for chemical treatment can be reduced substantially by IPM programs which employ antagonistic fungal species (135), blight and insect resistant cultivars, crop rotations, disease-free seed, and soil pH manipulation (139). In Colorado the use of a tachnid fly as a predator on the potato beetle has been shown to have potential to greatly reduce use of the insecticide aldicarb (140).

5.7 *SUMMARY OF PESTICIDE BMPS FOR MAJOR CROPS*

1. Corn

The greatest potential for reduction in pesticide losses from this crop involves reducing insecticide use. The major BMPs for accomplishing this include crop rotation to maintain insect pest populations at low levels, and adequate field monitoring so that pesticide applications are not made to fields which do not have pest problems. Crop rotation will also reduce herbicide needs to some extent. SWCPs have potential for significantly reducing pesticide losses from corn cropping because of the types of pesticides used and the fact that two-thirds of this crop is grown on moderately to highly erosive land (161). Improvements in pesticide application technique can reduce losses somewhat, but the potential is less than for some other major crops. Gross pesticide inputs to aquatic systems from this crop can be reduced between 60 and 80 percent using current technology.

2. Soybeans

The greatest challenge relating to insecticide contamination from soybean cropping is to prevent the emergence of new pest complexes as soybean production continues to spread into the South-east and South-central U.S. This can be accomplished by well-researched IPM programs. Reducing herbicide usage is accomplished most effectively by crop rotation, early planting, and precise application rates. Much more research on controlling soybean weed pests is needed.

An increasing amount of soybean acreage, especially in the south-central U.S., is being aerially sprayed, indicating potential for reducing field losses through application method improvements. SWCPs have some potential to augment pesticide loss reductions from IPM and improvements in application methods. Overall pesticide use and subsequent losses to aquatic systems are in danger of increasing over current levels. However, using current knowledge and anticipated advances in weed IPM, reductions in pesticide inputs to surface waters of 20-40 percent should be attainable.

3. Cotton

Dramatic reductions have been made in cotton insecticide usage through IPM programs. Further reductions are feasible through expanded IPM implementation. Significant reductions in drift and volatilization losses of pesticides can be accomplished most effectively by improvements in application method and timing. Weed IPM programs for cotton are still largely undeveloped. Herbicide use reductions at the present time are most effectively accomplished by crop rotation and precise application rate.

SWCPs have very limited potential compared to IPM and application improvements for reducing pesticide runoff losses because a majority of cotton is grown on fields with little slope and low erosion rates. Pesticide pollution of groundwater aquifers is the major water resource impairment in many cotton-growing areas; runoff-reducing SWCPs may exacerbate this problem depending on soil type, pesticide mobility, and depth to groundwater. Further overall reductions in pesticide use and field loss in the range of 50 to 75 percent are possible with current IPM and application technology.

4. Tobacco

Tobacco lands represent potentially intense sources of aquatic pesticide contamination because of the combination of intensive pesticide usage and the need for extensive surface drainage. Reducing pesticide use through expanded implementation of IPM programs appears to be the most effective and agronomically practical means of reducing pesticide inputs from this source. Overall reductions in pesticide inputs to aquatic systems should be almost directly proportional to reductions in application rates, estimated to be in the range of 40 to 60 percent with current knowledge and present economics of tobacco production.

5. Decidious Tree Fruits

Reduction in pesticide aquatic inputs (primarily fungicides) of 50 to 80 percent are attainable primarily through IPM.

Chapter 6

CONCLUSIONS

1. In some cases, there may be inherent tradeoffs between controlling pesticide loss and other agricultural pollutants. An example is no-tillage systems which reduce sediment losses but increase pesticide use and subsequent losses of volatile, and in some cases, runoff-carried pesticides.

2. For weakly to moderately bound pesticide types, management practices which reduce losses from surface runoff, drift or volatilization may increase the potential for groundwater contamination depending on soil type, topography and depth to water table.

3. Volatilization and drift with subsequent deposition appear to be the largest pathways by which pesticides reach aquatic systems. However, this input is diffuse relative to surface runoff leaving the relative importance unclear in terms of aquatic system impacts.

4. Even in cases where eliminating aerial application of pesticides is not feasible, options exist for improving the efficacy of such application methods; most notably, swath analysis, and timing based on meteorological conditions.

5. IPM and improved application efficiencies appear to be more effective than SWCPs in reducing pesticide inputs to aquatic systems. In some situations, however, such as on steeply sloping cropland directly adjacent to water courses, SWCPs will be the most effective means of reducing aquatic impacts.

6. Management techniques, such as avoiding runoff-prone formulations (wettable powders, microgranules) and restricting application when storm events are anticipated, may be more cost effective than SWCPs for controlling runoff losses of pesticides.

7. Losses of pesticides which are transported almost entirely in the sediment phase of runoff, such as toxaphene, other organochlorines, and paraquat can be reduced by sediment control BMPs. However, the ex-

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tent of reduction is somewhat less than the sediment reduction because of the disproportionate amounts adsorbed on small sediment particles which are less controlled by sediment control BMPs.

8. Recent pest control trends indicate that the most cost effective method of reducing environmental impacts of toxaphene is the substitution of synthetic pyrethroids, especially on cotton.

9. For pesticides such as the carbamates, organophosphates, triazines and anilides which are lost primarily in the dissolved phase of runoff, losses to surface waters will be decreased by the use of runoff-reducing practices including terraces, contouring, and in some cases, reduced tillage.

10. Conservation tillage systems as runoff-reducing practices do not always result in reduction of pesticide losses in runoff. The decrease in runoff volume is at least partially, and in some cases completely, negated by the increased availability of pesticides on surface residue. If the first runoff event after application is very large, greater losses are usually observed from conservation tillage systems; if the first event is small, conservation tillage systems usually exhibit much lower pesticide losses than conventional systems.

11. In terms of gross amounts, application efficiency improvements can probably reduce pesticide field losses more than SWCPs or IPM. However, drift and volatilization losses are generally more diffuse, and further research is needed to evaluate their relative significance to aquatic systems.

12. The potential of IPM programs to reduce chemical pesticide usage and subsequent loss to the surrounding environment continues to be great. Use reduction potential based on current and developing technology, however, varies greatly with crop. Tremendous reduction are feasible for corn and deciduous fruits, while only moderate reductions can be expected for soybeans.

13. Cotton pesticide use has fallen 75-80% since 1976. Further reductions are anticipated but will be less dramatic.

14. The trend of increasing use of ultra-low-volume (ULV) pesticide formulations should be discouraged as these formulations contribute to an increase in drift losses of pesticides.

15. From the viewpoint of minimizing environmental losses of pesticides aerial spraying is uniformly undesirable, and alternative methods should be used whenever possible.

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